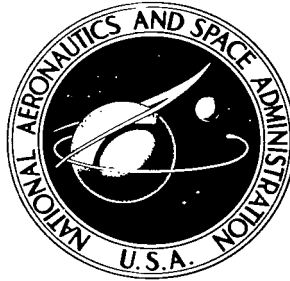


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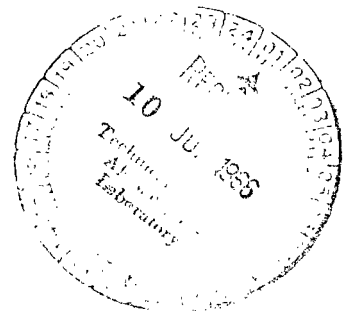
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CHARTS OF ADDITIVE DRAG COEFFICIENT
AND MASS-FLOW RATIO FOR INLETS
UTILIZING RIGHT CIRCULAR CONES
AT ZERO ANGLE OF ATTACK

by Vincent R. Mascitti

Langley Research Center

Langley Station, Hampton, Va.





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SUMMARY

Working charts are presented giving values of additive drag coefficient and mass-flow ratio for inlets utilizing axisymmetric cones at zero angle of attack. Cone half-angles range from 5° to 35° . The free-stream Mach number ranges from that which will yield sonic flow on the cone surface to 12. Perfect-gas relations are used throughout the calculations.

INTRODUCTION

The treatment of additive drag in reference 1 includes a study of axisymmetric inlets for a limited range of free-stream Mach numbers and cone half-angles which were of primary interest at the time the study was made. Utilizing axisymmetric inlets for hypersonic vehicles requires data over a larger range of Mach numbers and at smaller cone half-angles. Calculations for such data have been made and are presented herein as working charts for a range of Mach numbers from that which will yield sonic flow on the cone surface to 12, and for cone half-angles from 5° to 35° .

The computation of additive drag was accomplished by numerical integration of the pressures existing along the entering stream tube. The mass-flow ratios were determined from the radial coordinates of the streamline which corresponded to the limits of the pressure integration. The computations of the additive drag and the mass-flow ratio were made by adding a subroutine to a machine computer program which was used to calculate conical flow parameters. The computations of the present paper cover the ranges of variables presented in reference 1 in order that a complete set of data may be obtained from one source. It may be noted from a comparison of the two sets of results that some differences in shock angles exist. The shock angles computed herein agree with those presented in reference 2.

SYMBOLS AND NOTATIONS

A	cross-sectional area
$C_{D,a}$	additive drag coefficient, $\frac{D_a}{qA}$
D_a	additive drag
K	defined parameter, $\frac{(1 - W_1^2)^{\frac{1}{\gamma-1}} W_{N,1}}{\sin \theta_1}$
L	integration index for cowl location
M	Mach number
w	mass flow
w/w_0	ratio of mass flow entering inlet to that passing through area A under free-stream conditions
p	pressure
q	dynamic pressure, $\frac{\gamma}{2} p_0 M_0^2$
r	radius
S	conical area generated by revolution of a ray
t	temperature
V	velocity of flow
V_{lim}	limiting velocity obtained by expanding flow to zero temperature
W	ratio of local velocity to limiting velocity, $\frac{V}{V_{lim}}$
z	distance along generatrix ray
γ	ratio of specific heats, 1.400 for air
2	

η cone half-angle

θ ray angle

ρ density

Subscripts:

0 conditions upstream of conical shock

1 conditions just downstream of conical shock

c conditions on cone surface

J numerical integration index

l conditions at cowl location

N conditions normal to shock or ray

t stagnation conditions

METHOD OF SOLUTION

The solution of the flow field around cones at zero angle of attack has been published in references 3 and 4 and, therefore, will not be repeated herein. In the present investigation, the solution of the conical flow problem was derived by the use of an existing computer program in a manner similar to that of reference 3. Outputs were normal and resultant velocity ratio (W_N/W) for a given ray angle, cone half-angle, and free-stream Mach number (θ, η, M_0). The values of free-stream Mach number for sonic flow on the cone surface were taken from table 1 of reference 5.

For conical flow, the transition across the shock wave is governed by the oblique shock relations and followed by a continuous isentropic compression to surface conditions. Figure 1 shows a diagram of the flow field and additive drag parameters. The conditions just downstream of the shock and the coordinates of a point on the entering streamline must be defined in order to determine the mass-flow ratio.

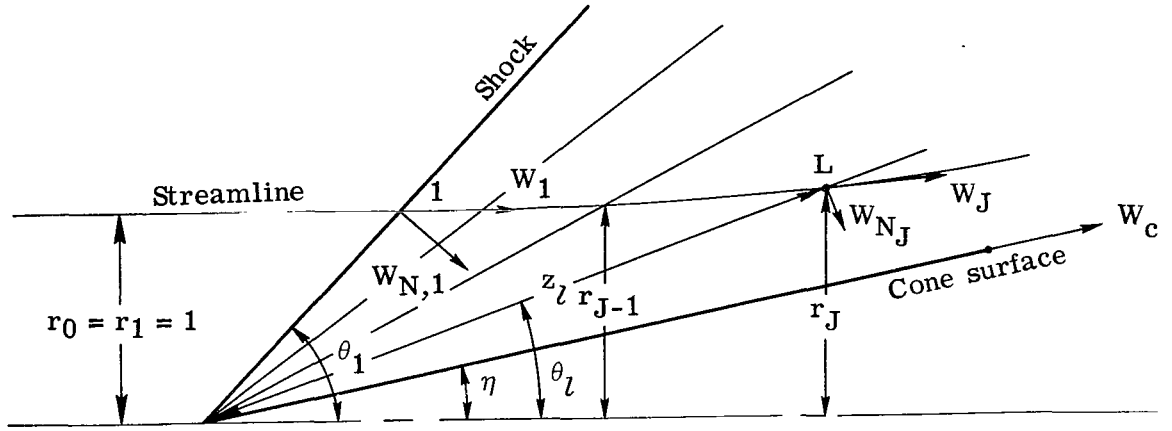


Figure 1.- Diagram showing flow field and additive drag parameters.

The mass flow at any position downstream of the shock is given by

$$w = \rho_l W_{N,l} S_l = \rho_1 W_{N,1} S_1$$

If the following relations are assumed:

$$S_l = \pi r_l z_l$$

$$r_l = z_l \sin \theta$$

$$r_1 = 1$$

$$\left(\frac{\rho}{\rho_t} \right)_l = \left(1 - W_l^2 \right)^{\frac{1}{\gamma-1}}$$

the distance along a generatrix ray required to pass the mass flow $\rho_1 W_{N,1} S_1$ is

$$z_l = \sqrt{\frac{K}{\left(1 - W_l^2 \right)^{\frac{1}{\gamma-1}} W_{N,l} \sin \theta_l}}$$

where $K = \frac{1}{\sin \theta_1} \left(1 - W_1^2\right)^{\frac{\gamma-1}{2}} W_{N,1}$, a convenient parameter defined only by conditions across the shock. The mass-flow ratio captured by a cowl lip at position l is defined as follows:

$$\frac{w}{w_0} = \frac{\rho_0 V_0 A_0}{\rho_0 V_0 A_l}$$

If $A_l = \pi r_l^2$ and $r_1 = r_0 = 1$, then

$$\frac{w}{w_0} = \frac{1}{r_l^2} \quad (1)$$

Additive drag is defined in reference 1 as

$$D_a = \int_1^L (p - p_0) dA \quad (2)$$

Equation (2) may be approximated by the method of numerical integration in the form:

$$D_a = \sum_{J=2}^L \left(\frac{p_J + p_{J-1}}{2} - p_0 \right) (A_J - A_{J-1}) \quad (3)$$

The additive drag coefficient is given by

$$C_{D,a} = \frac{D_a}{q A_l}$$

Substituting equivalent expressions for the parameters in this equation and rearranging yield

$$C_{D,a} = \frac{1}{\gamma M_0^2 r_l^2} \sum_{J=2}^L \left(\frac{p_J}{p_0} + \frac{p_{J-1}}{p_0} - 2 \right) (r_J^2 - r_{J-1}^2)$$

where

$$\frac{p_J}{p_0} = \left(\frac{p_1}{p_0} \right) \left[\frac{(p/p_t)_J}{(p/p_t)_1} \right]$$

and, from reference 2,

$$\frac{p_1}{p_0} = \frac{2\gamma M_0^2 \sin^2 \theta_1 - (\gamma - 1)}{\gamma + 1}$$

$$\left(\frac{p}{p_t}\right)_J = \left(1 - W_J^2\right)^{\frac{\gamma}{\gamma-1}}$$

The drag coefficient on the cone surface is given by

$$C_{D,c} = \frac{2}{\gamma M_0^2} \left(\frac{p_c}{p_0} - 1\right)$$

where

$$\frac{p_c}{p_0} = \frac{p_1/p_0}{(p/p_t)_1} \left(1 - W_c^2\right)^{\frac{\gamma}{\gamma-1}}$$

Values of the cone drag coefficient are presented in the charts for which $\theta_l = \eta$.

In order to obtain sufficient accuracy, a 0.1° ray angle increment for numerical integration was chosen. Increments smaller than 0.1° showed no significant improvement in accuracy.

Perfect-gas relations ($\gamma = 1.4$) are assumed for the calculations herein, but at the higher Mach numbers and cone half-angles this assumption is not correct. The curve in figure 2 indicates the limitations imposed by the assumption. This figure shows the relationship between the cone half-angle and Mach number for which the surface static temperature is 1000° R (556° K). At this temperature the value of γ is 98 percent of the ideal value. At $M = 12$, for example, the cone half-angle can be 11.5° without exceeding this temperature limitation. Since at hypersonic speeds the conical half-angles of interest are usually

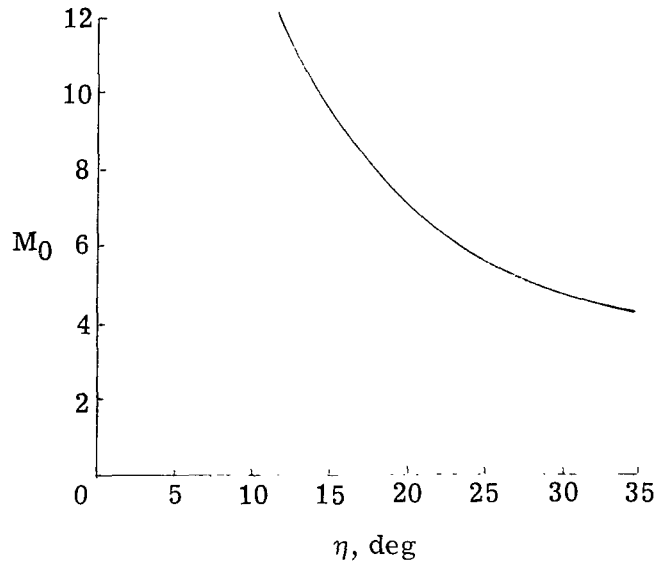
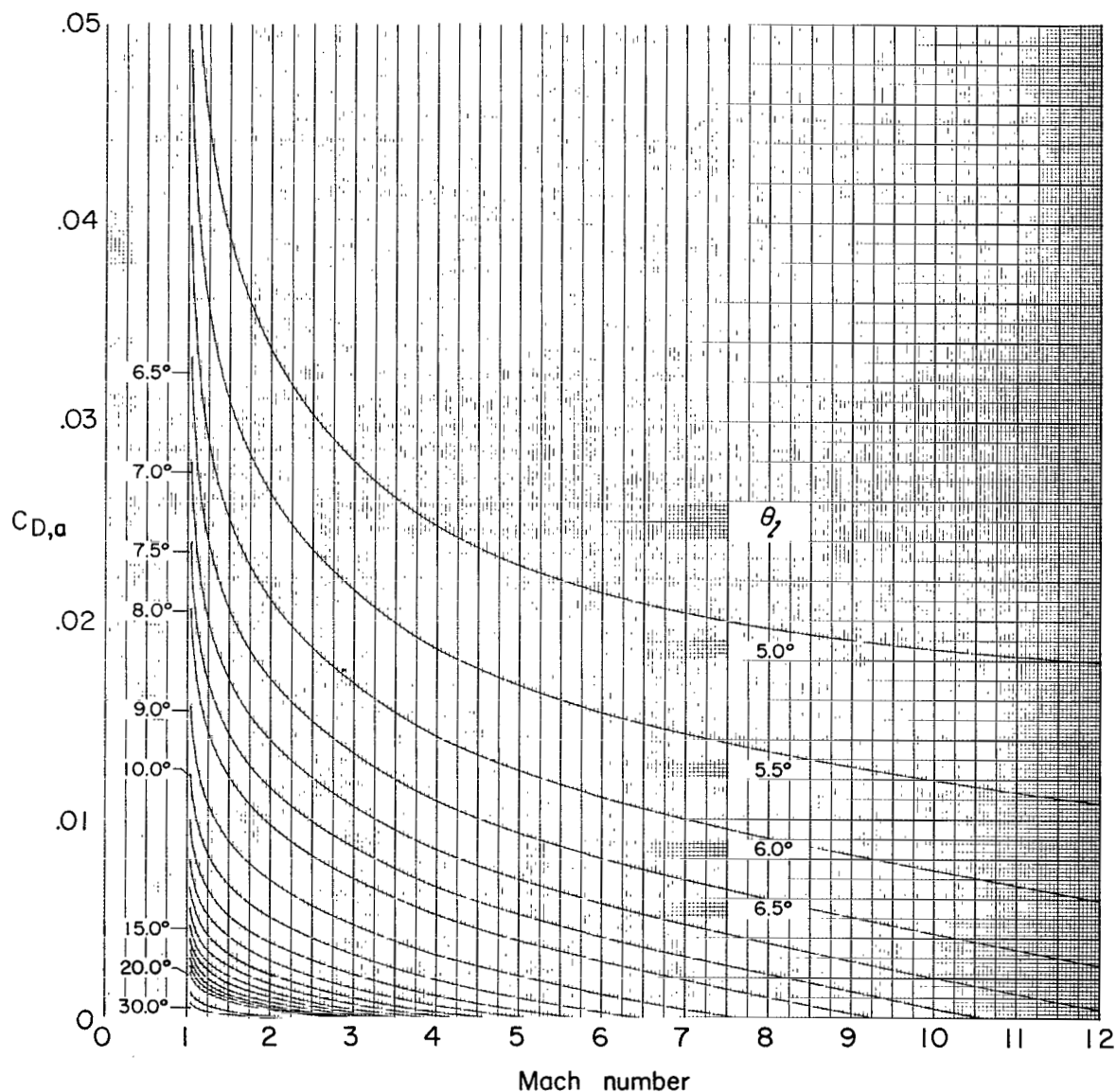


Figure 2.- Variation of free-stream Mach number with cone half-angle for $t_c = 1000^\circ \text{ R}$ (556° K).

less than 10° , expansion of the computation to include effects of the specific-heat ratio was not considered necessary.

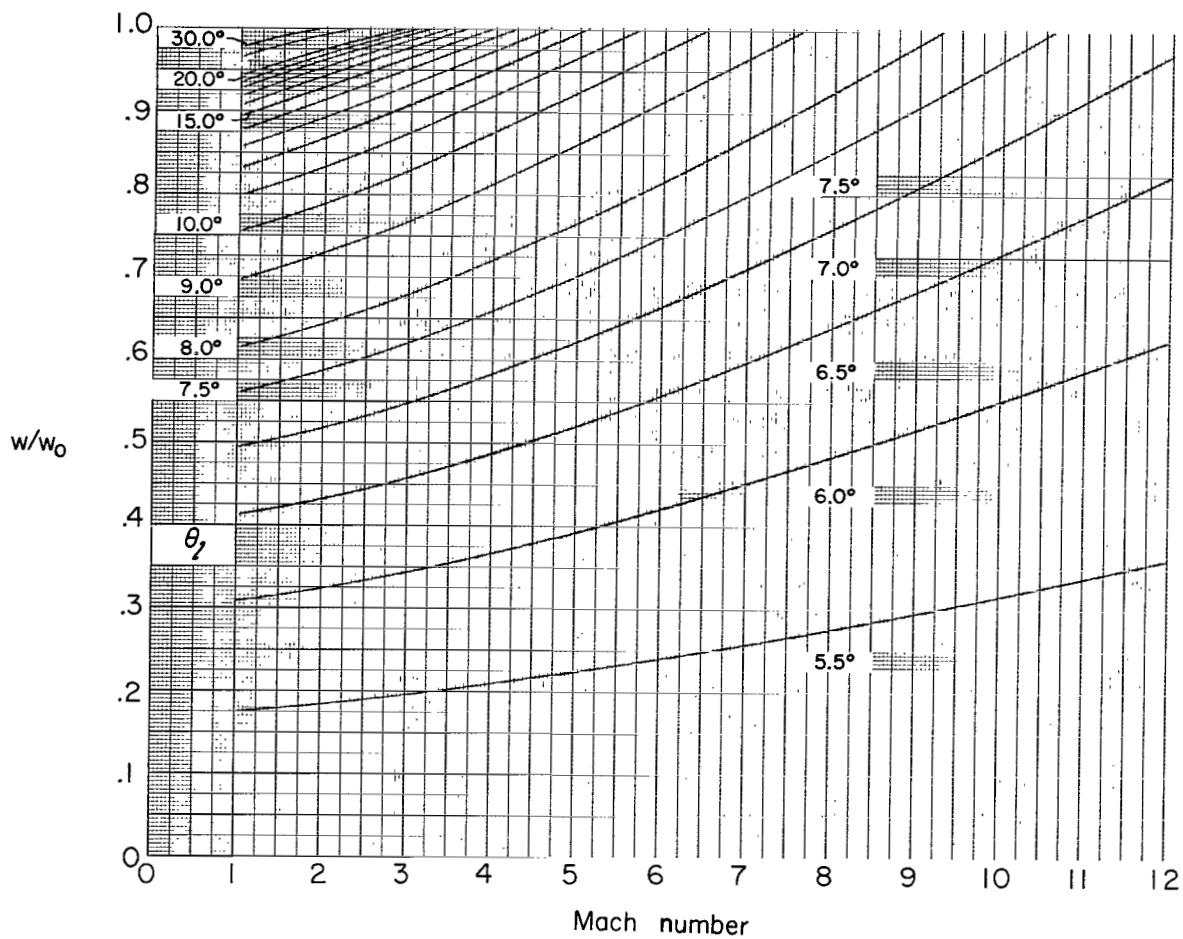
PRESENTATION OF CHARTS

Working charts are presented for cone half-angles between 5° and 35° in figures 3 to 14. For each cone half-angle, the additive drag coefficient is plotted as a function of the free-stream Mach number and the ray angle; the mass-flow ratio is plotted as a function of the free-stream Mach number and the ray angle; and the additive drag coefficient is plotted as a function of the mass-flow ratio for selected free-stream Mach numbers.



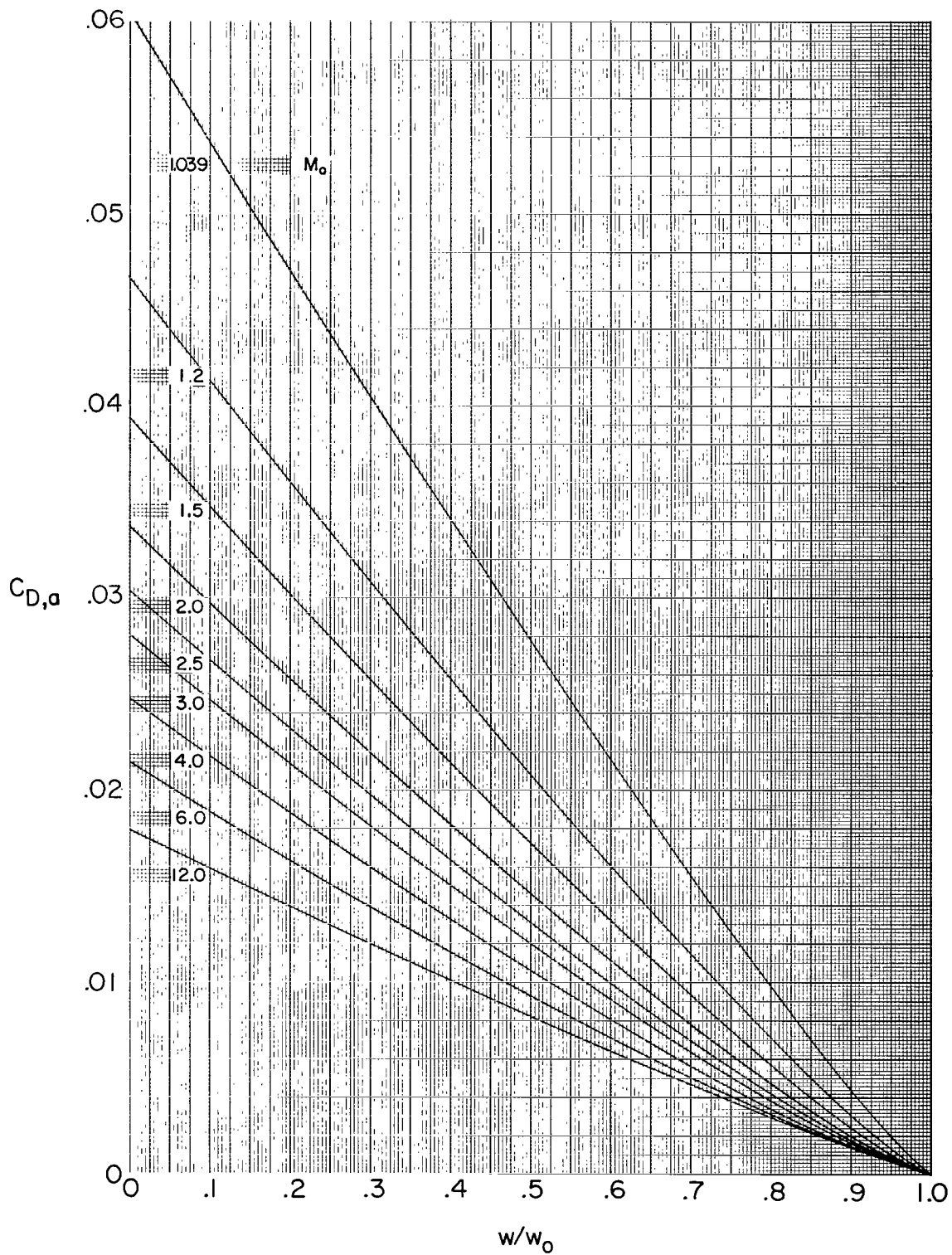
(a) Variation of additive drag with Mach number.

Figure 3.- Variation of additive drag and mass-flow ratio for $\eta = 5^\circ$.



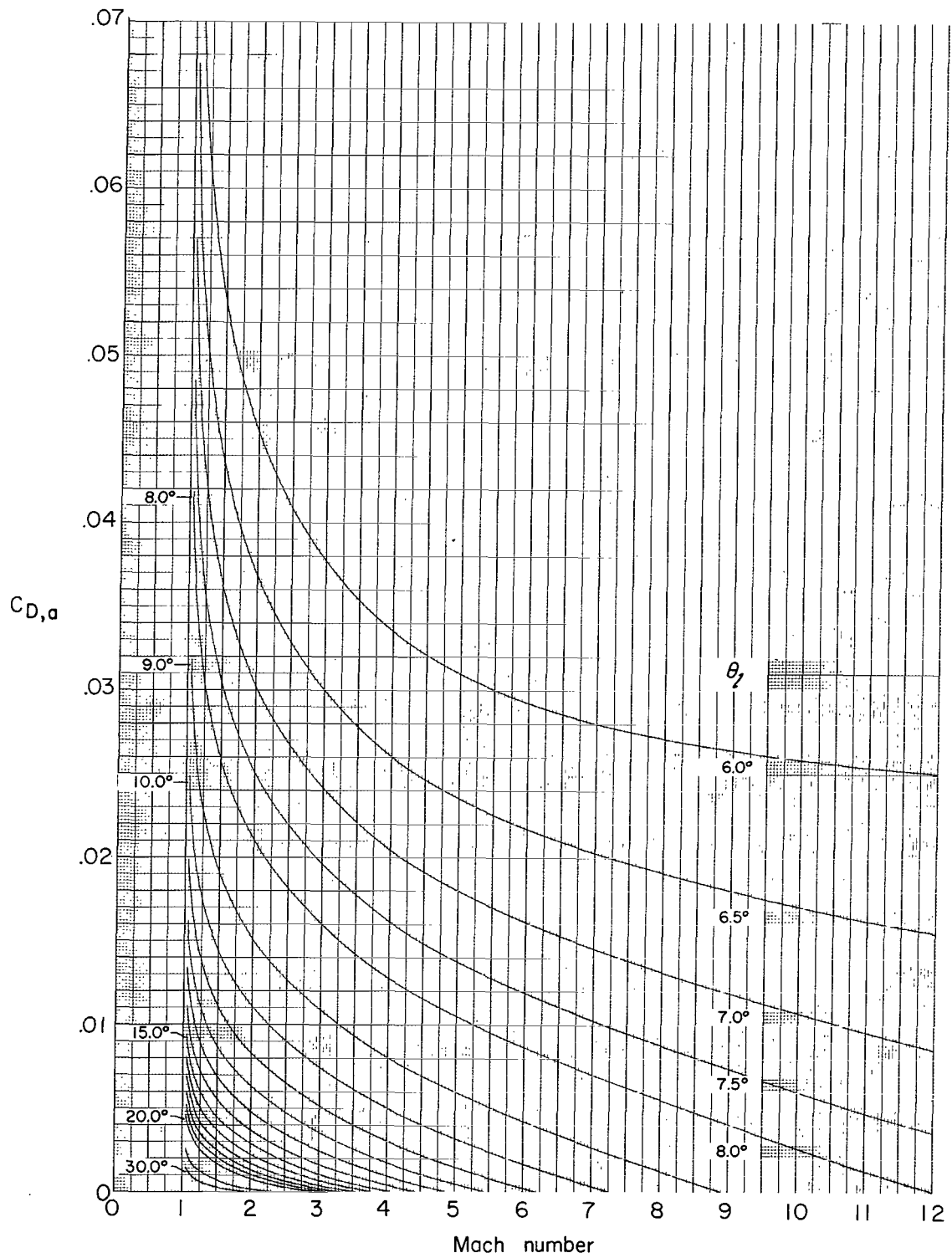
(b) Variation of mass-flow ratio with Mach number.

Figure 3.- Continued.



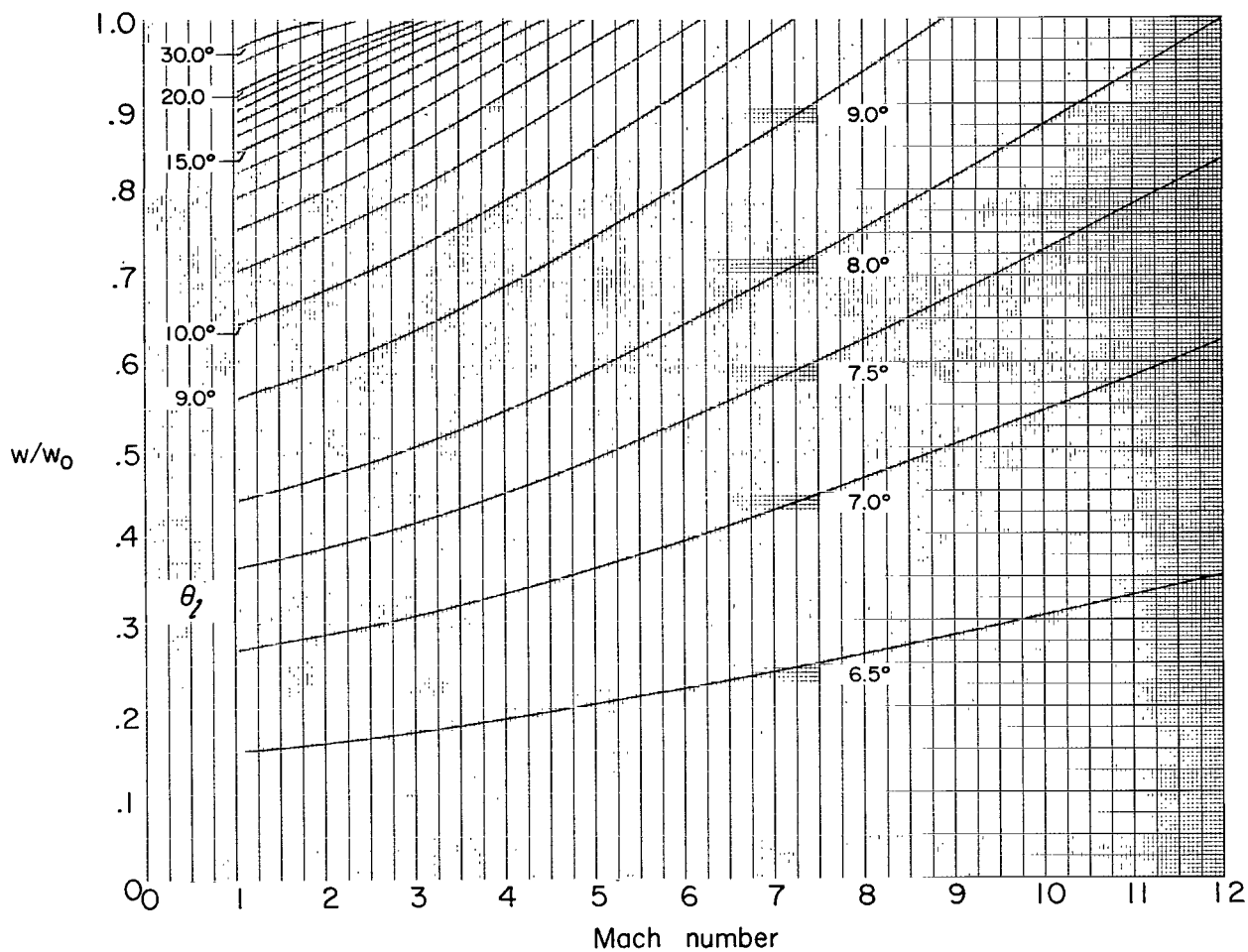
(c) Variation of additive drag with mass-flow ratio.

Figure 3.- Concluded.



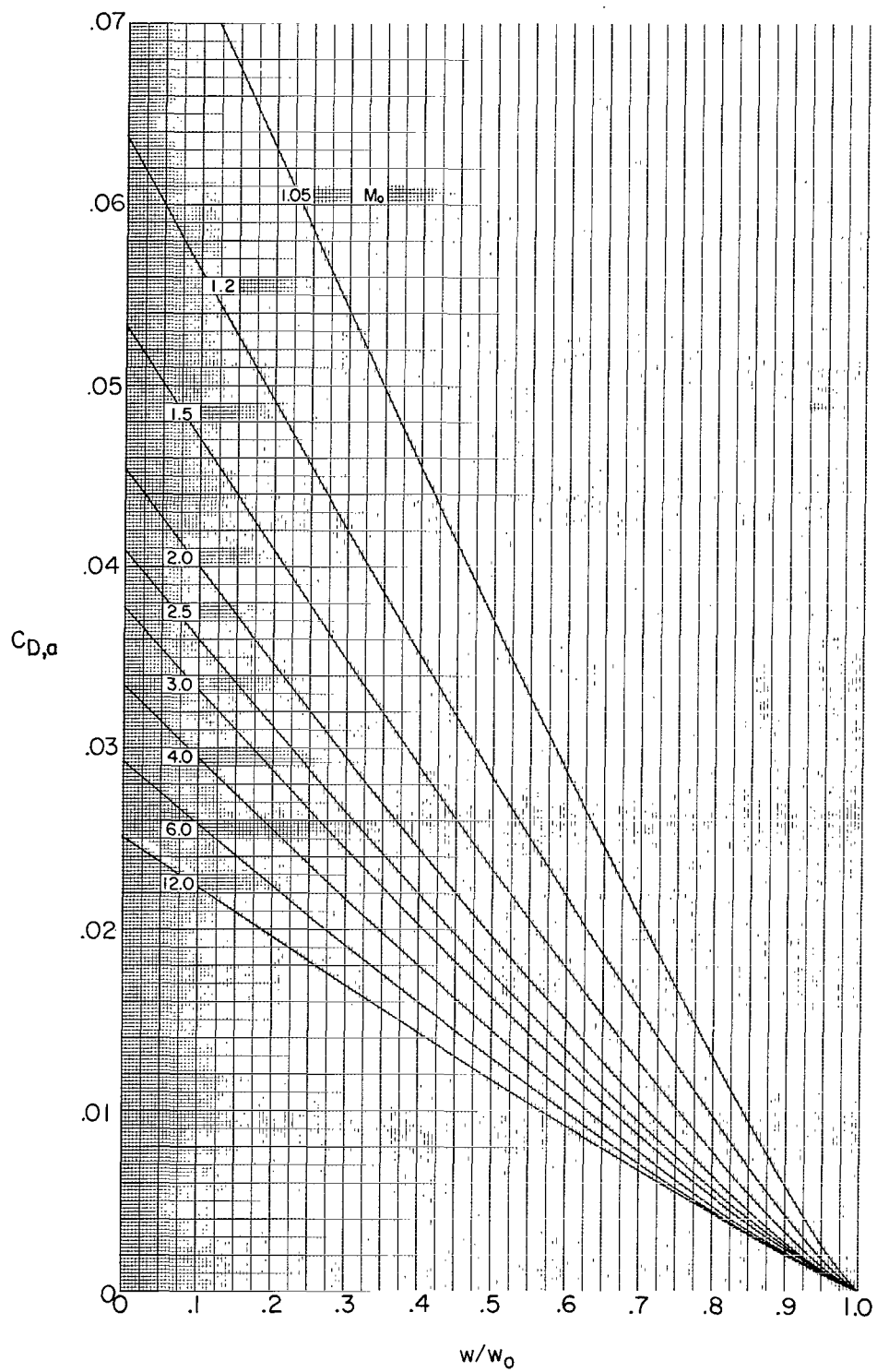
(a) Variation of additive drag with Mach number.

Figure 4.- Variation of additive drag and mass-flow ratio for $\eta = 60^\circ$.



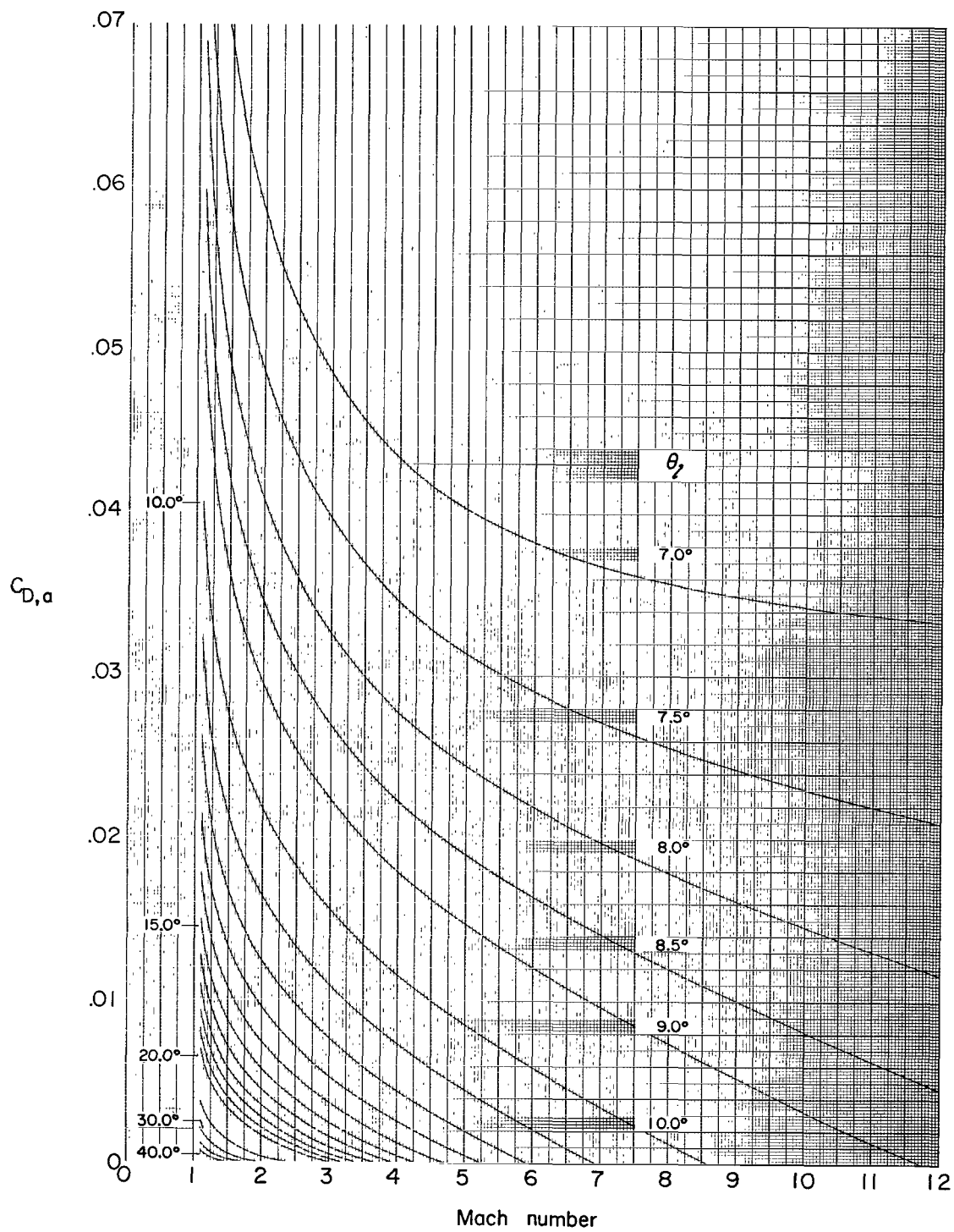
(b) Variation of mass-flow ratio with Mach number.

Figure 4.- Continued.



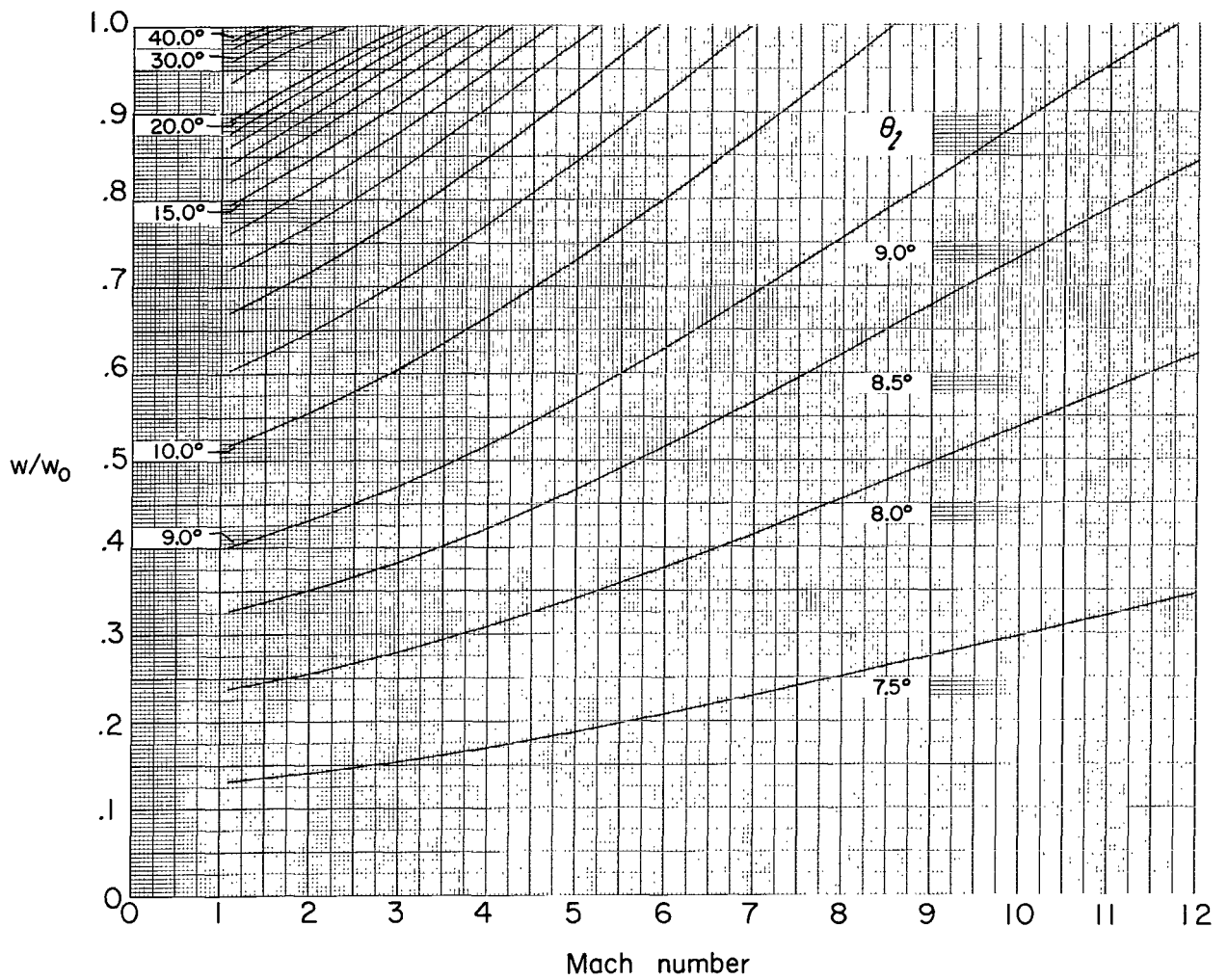
(c) Variation of additive drag with mass-flow ratio.

Figure 4.- Concluded.



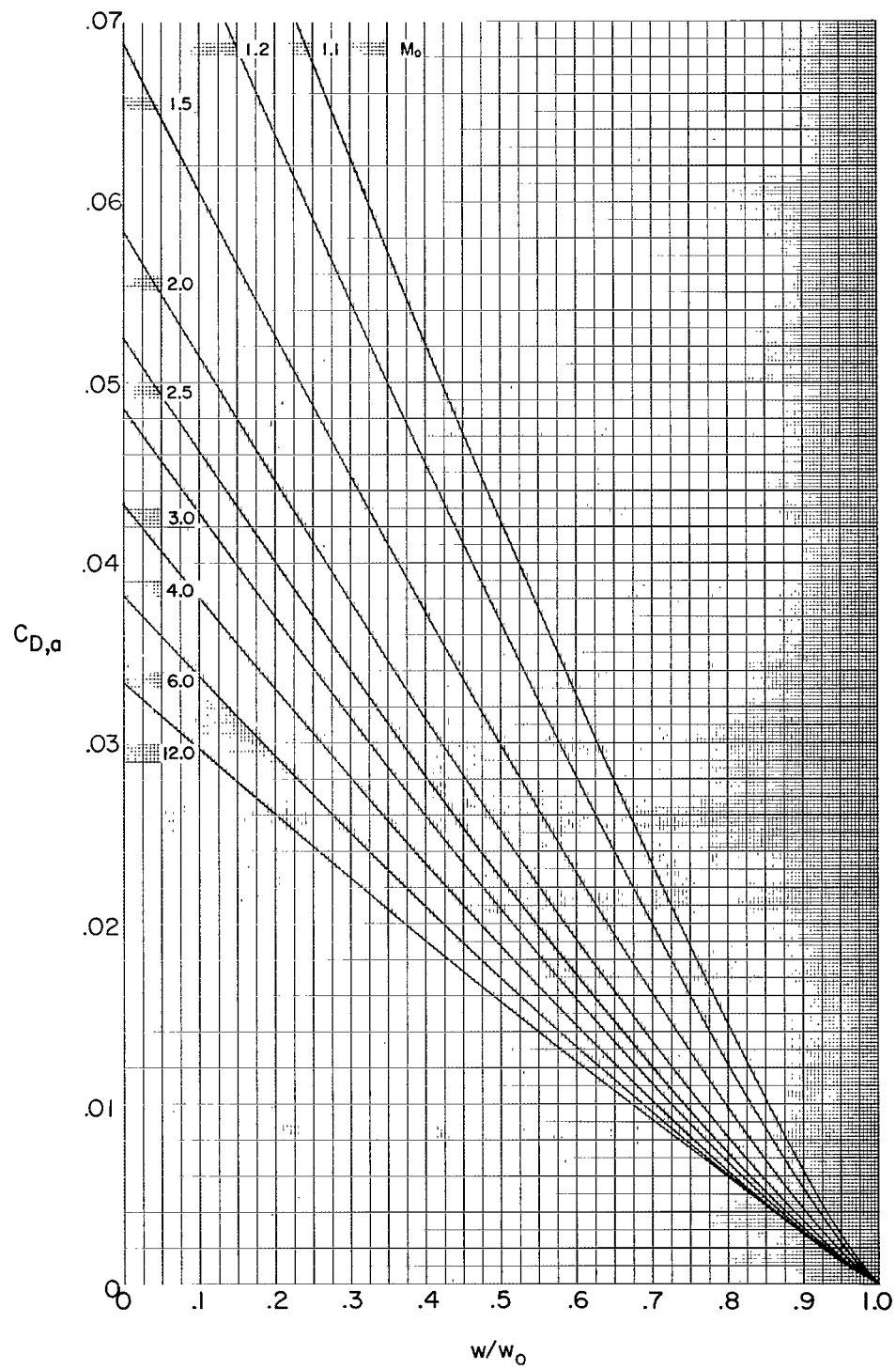
(a) Variation of additive drag with Mach number.

Figure 5.- Variation of additive drag and mass-flow ratio for $\eta = 7^\circ$.



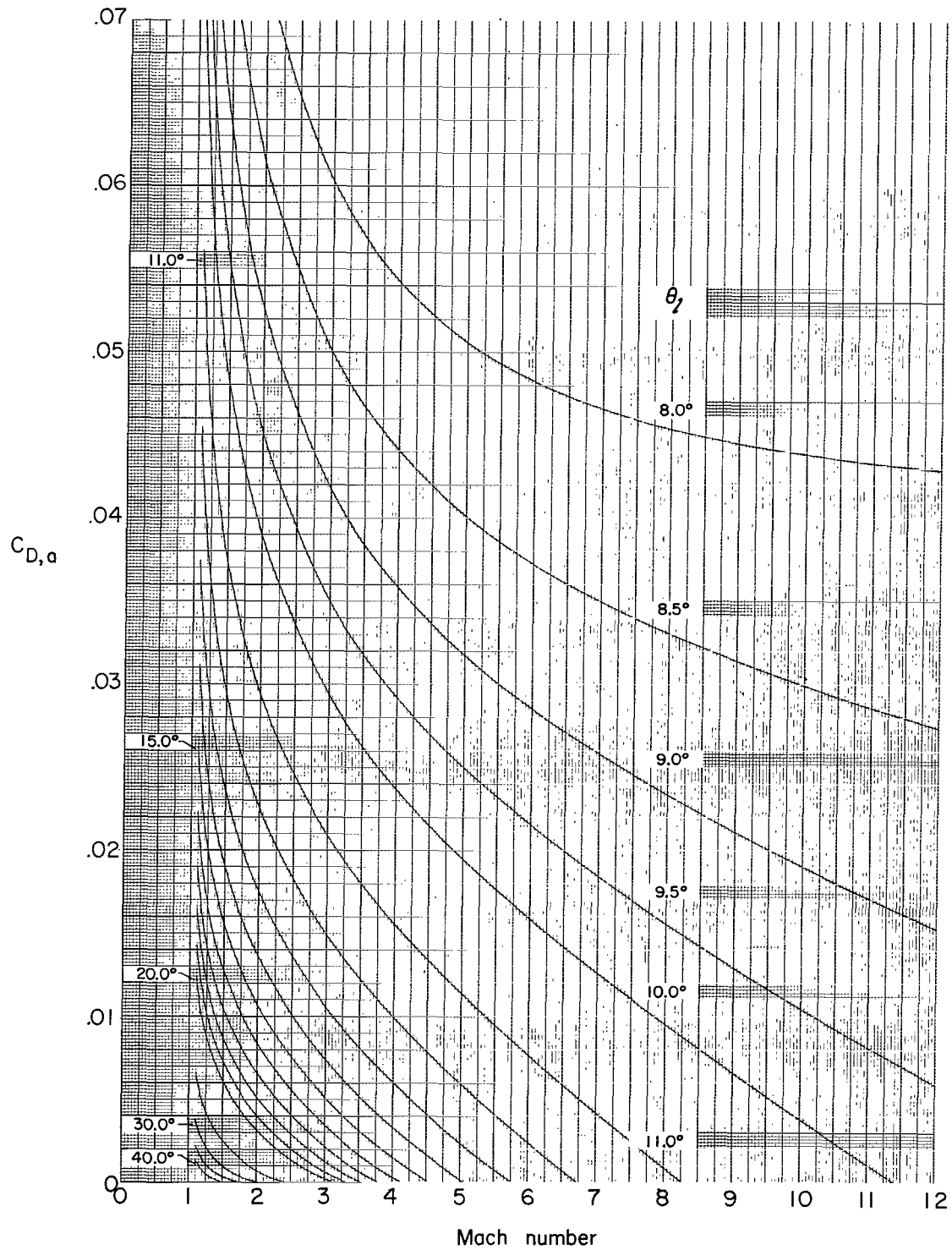
(b) Variation of mass-flow ratio with Mach number.

Figure 5.- Continued.



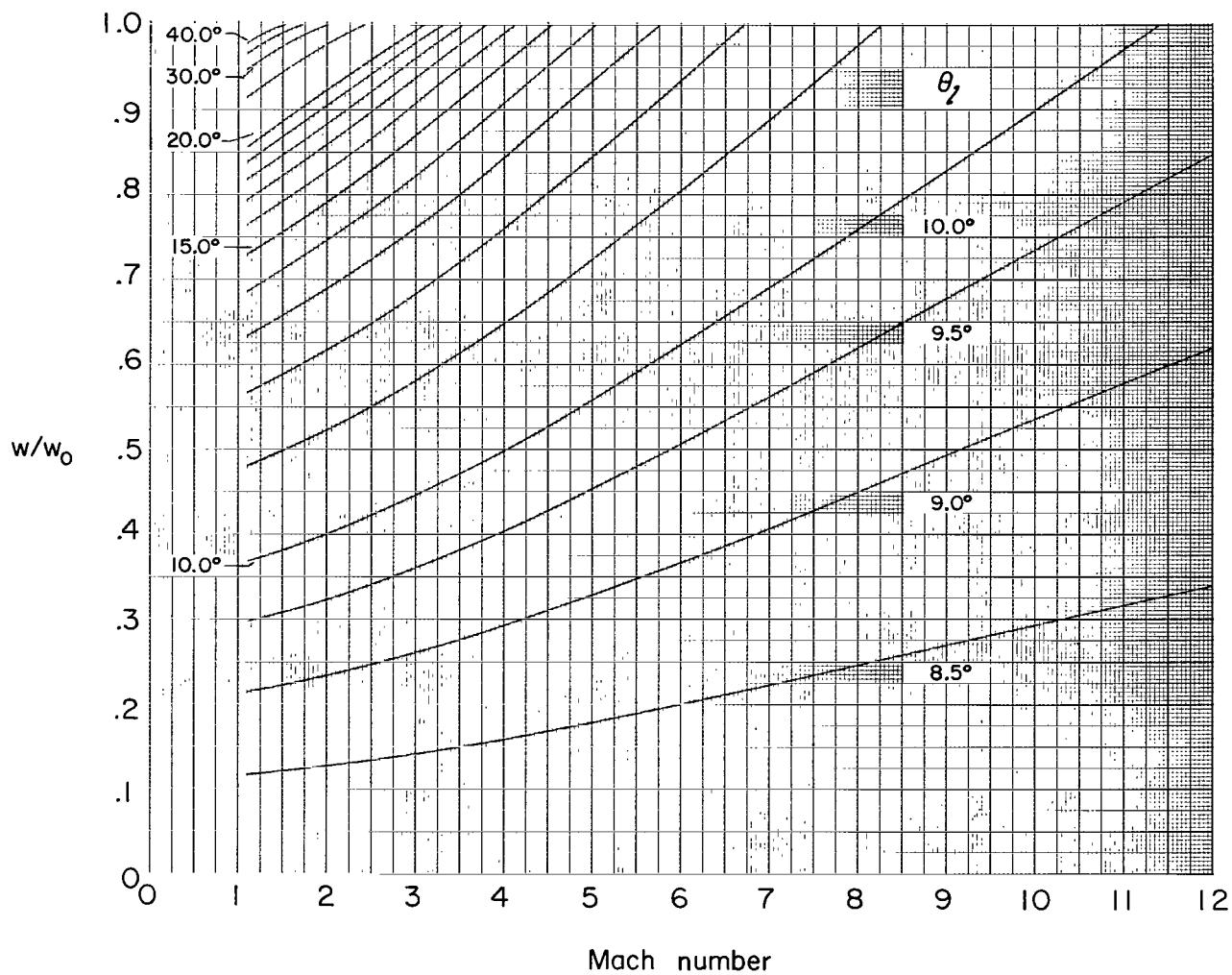
(c) Variation of additive drag with mass-flow ratio.

Figure 5.- Concluded.



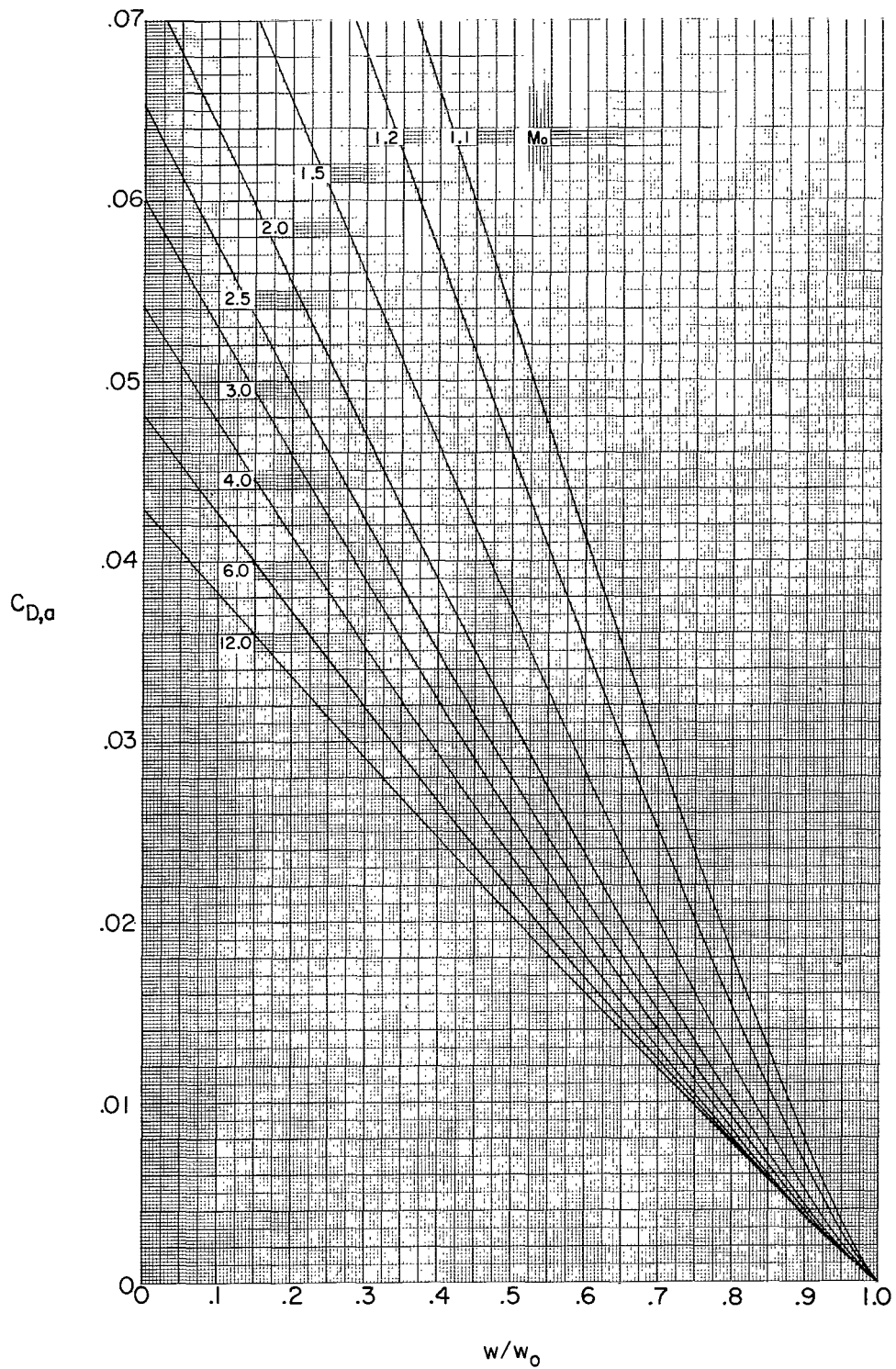
(a) Variation of additive drag with Mach number.

Figure 6.- Variation of additive drag and mass-flow ratio for $\eta = 80$.



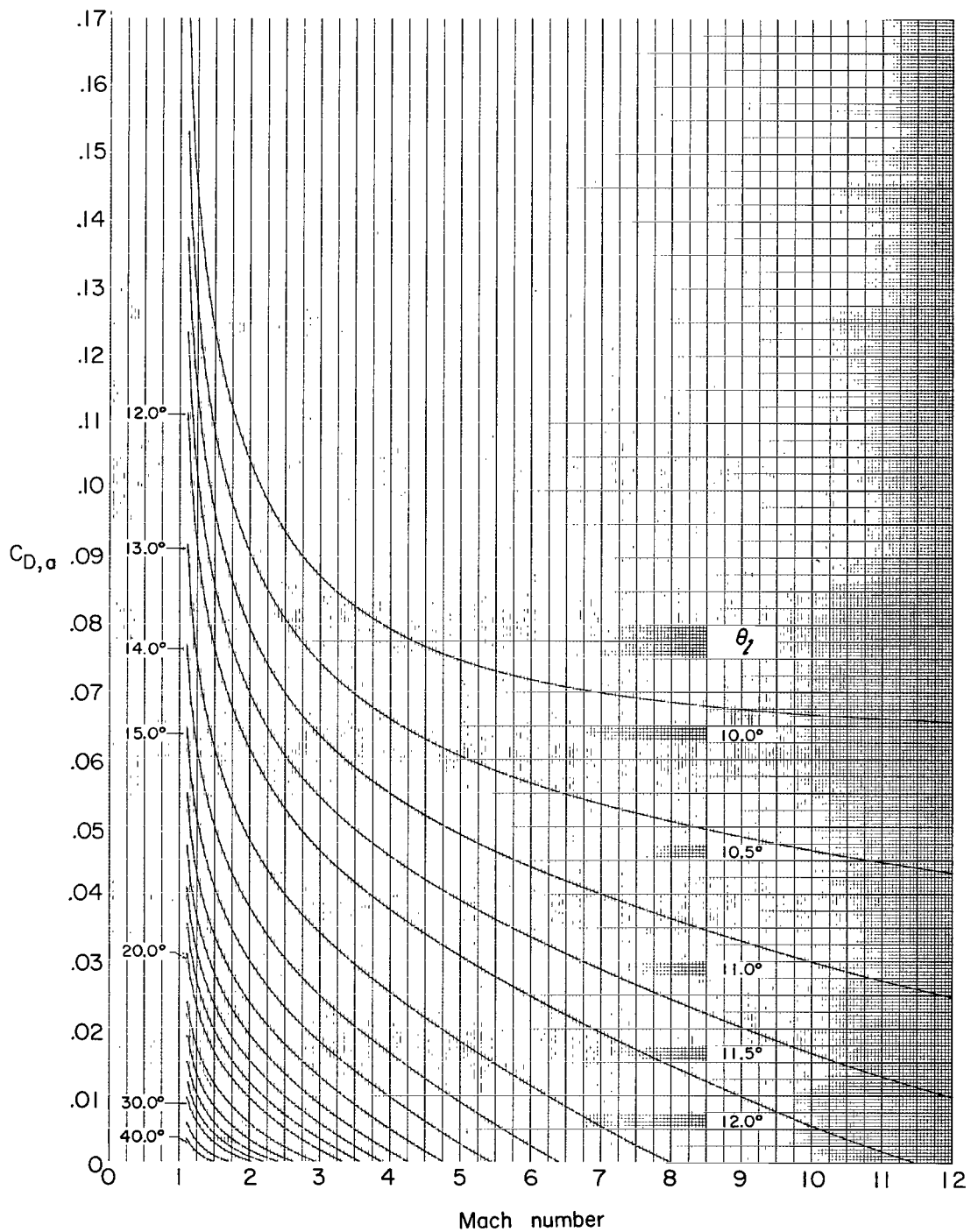
(b) Variation of mass-flow ratio with Mach number.

Figure 6.- Continued.



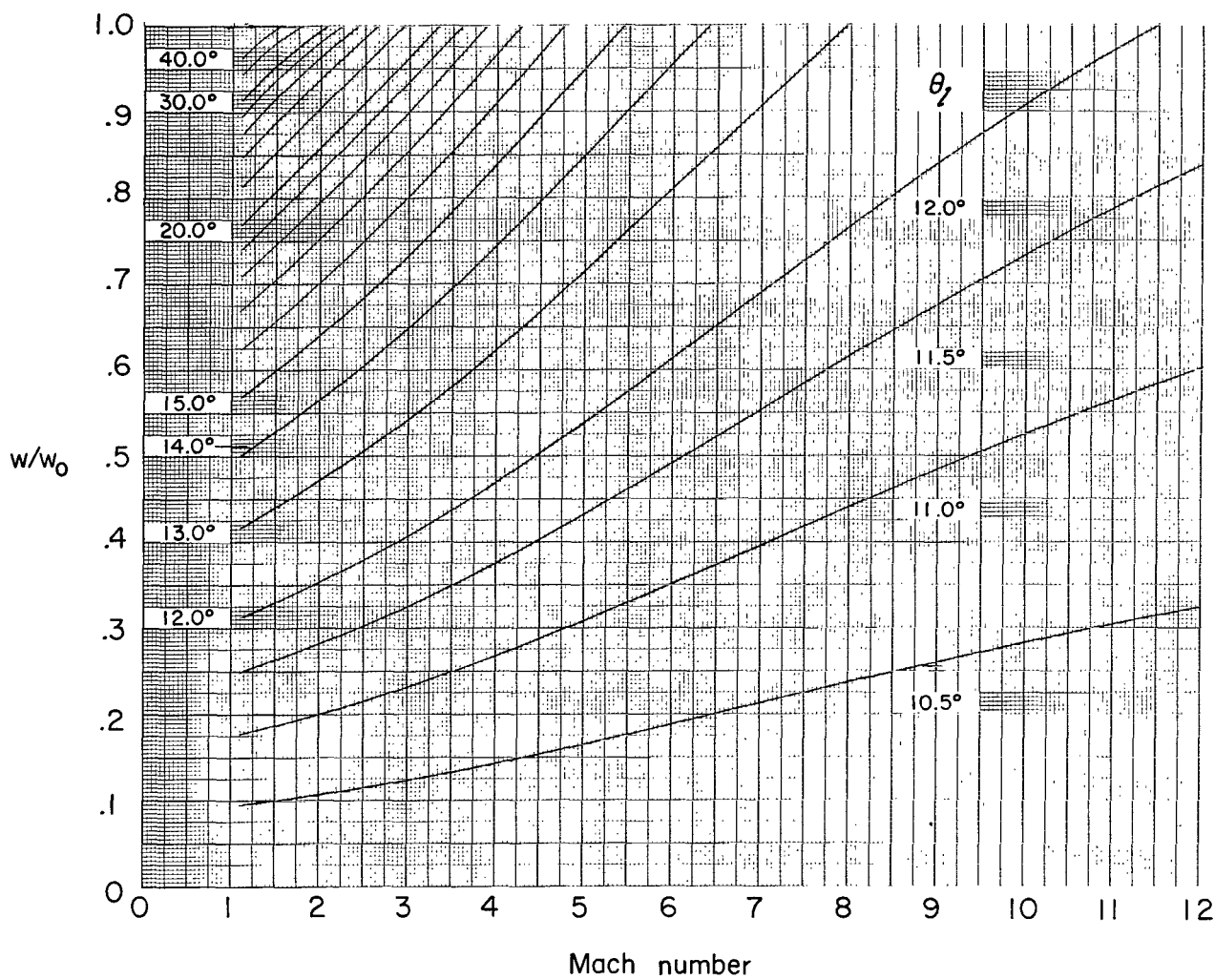
(c) Variation of additive drag with mass-flow ratio.

Figure 6.- Concluded.



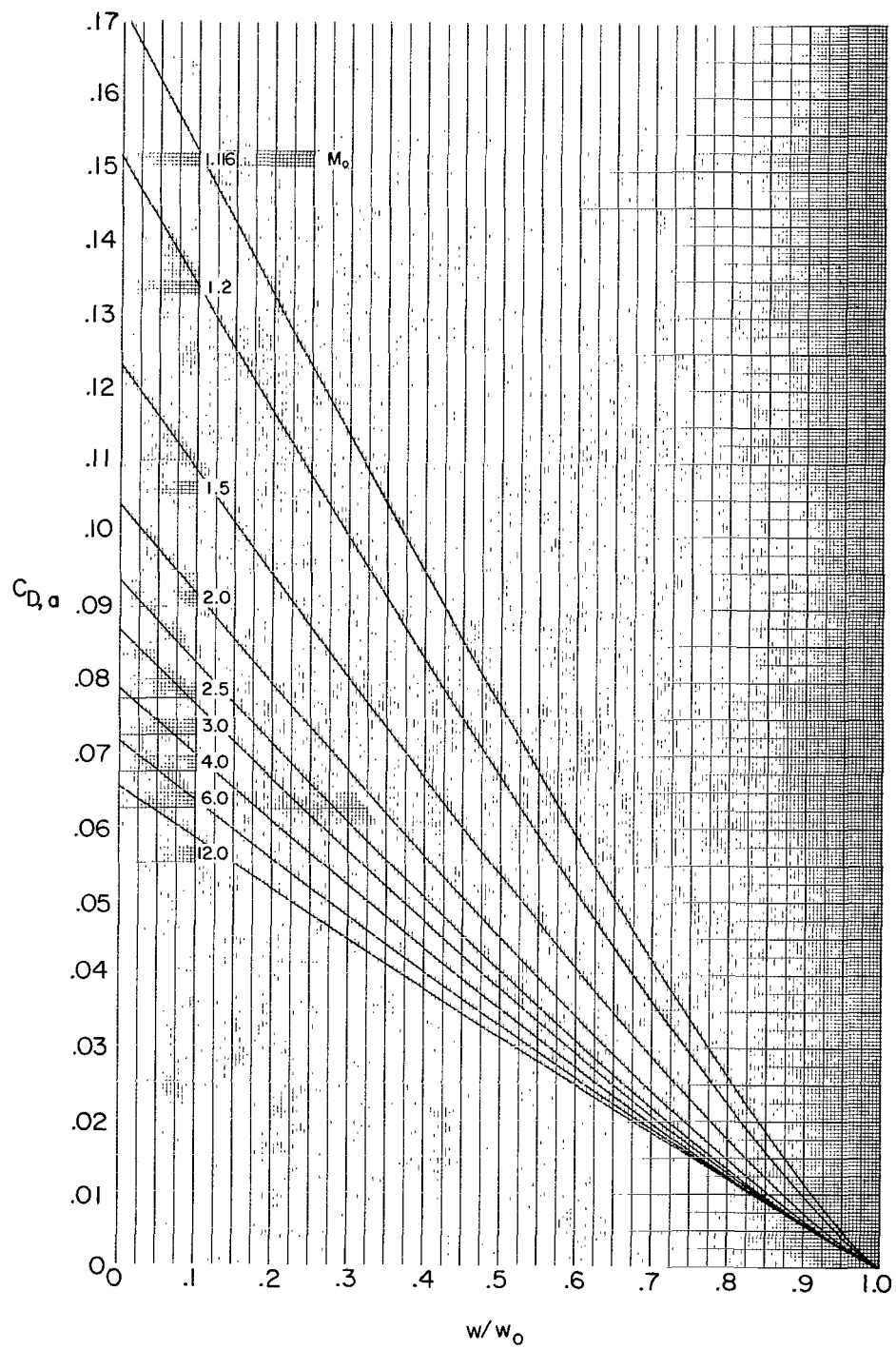
(a) Variation of additive drag with Mach number.

Figure 7.- Variation of additive drag and mass-flow ratio for $\eta = 100^\circ$.



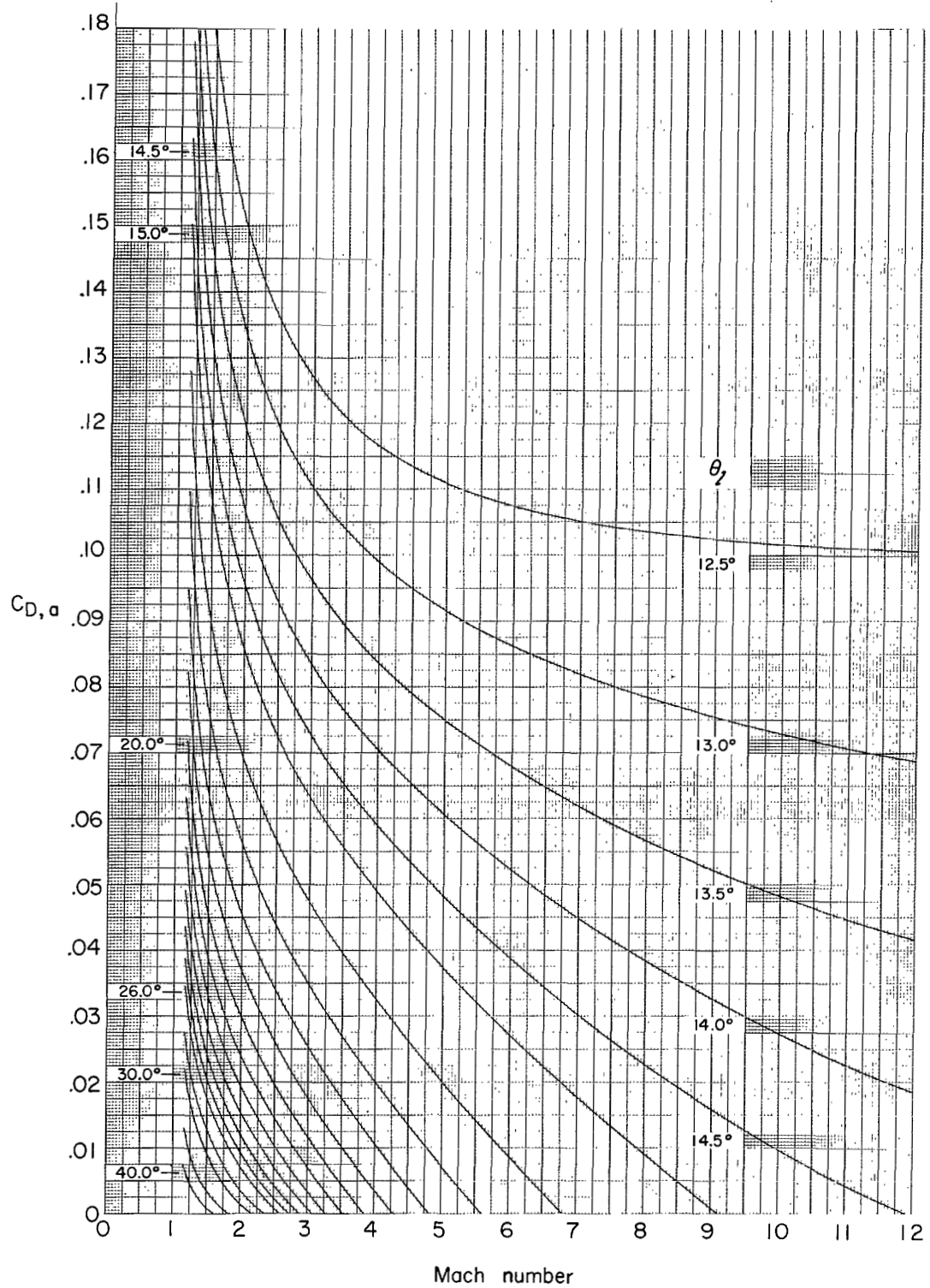
(b) Variation of mass-flow ratio with Mach number.

Figure 7.- Continued.



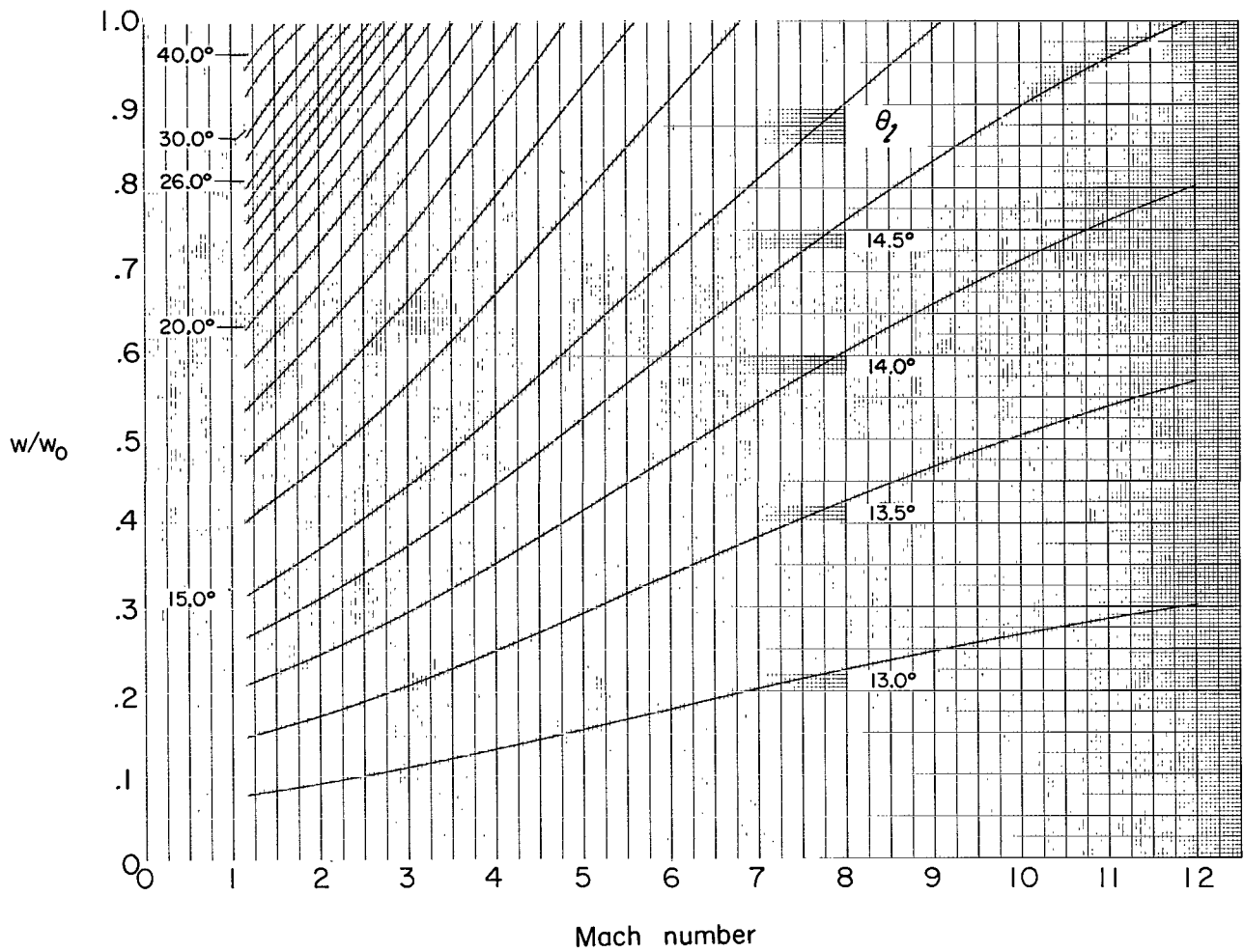
(c) Variation of additive drag with mass-flow ratio.

Figure 7.- Concluded.



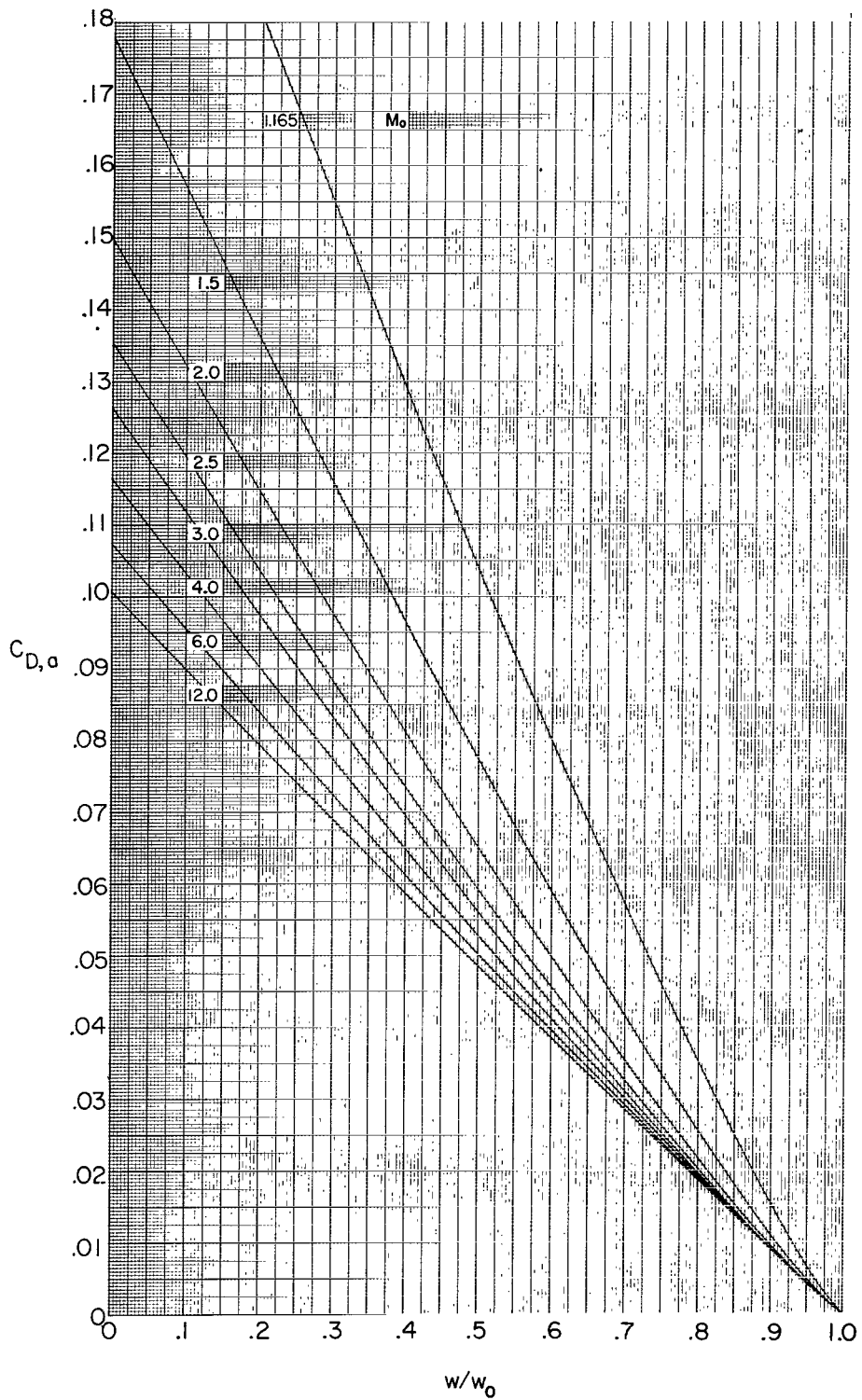
(a) Variation of additive drag with Mach number.

Figure 8.- Variation of additive drag and mass-flow ratio for $\eta = 12.5^\circ$.



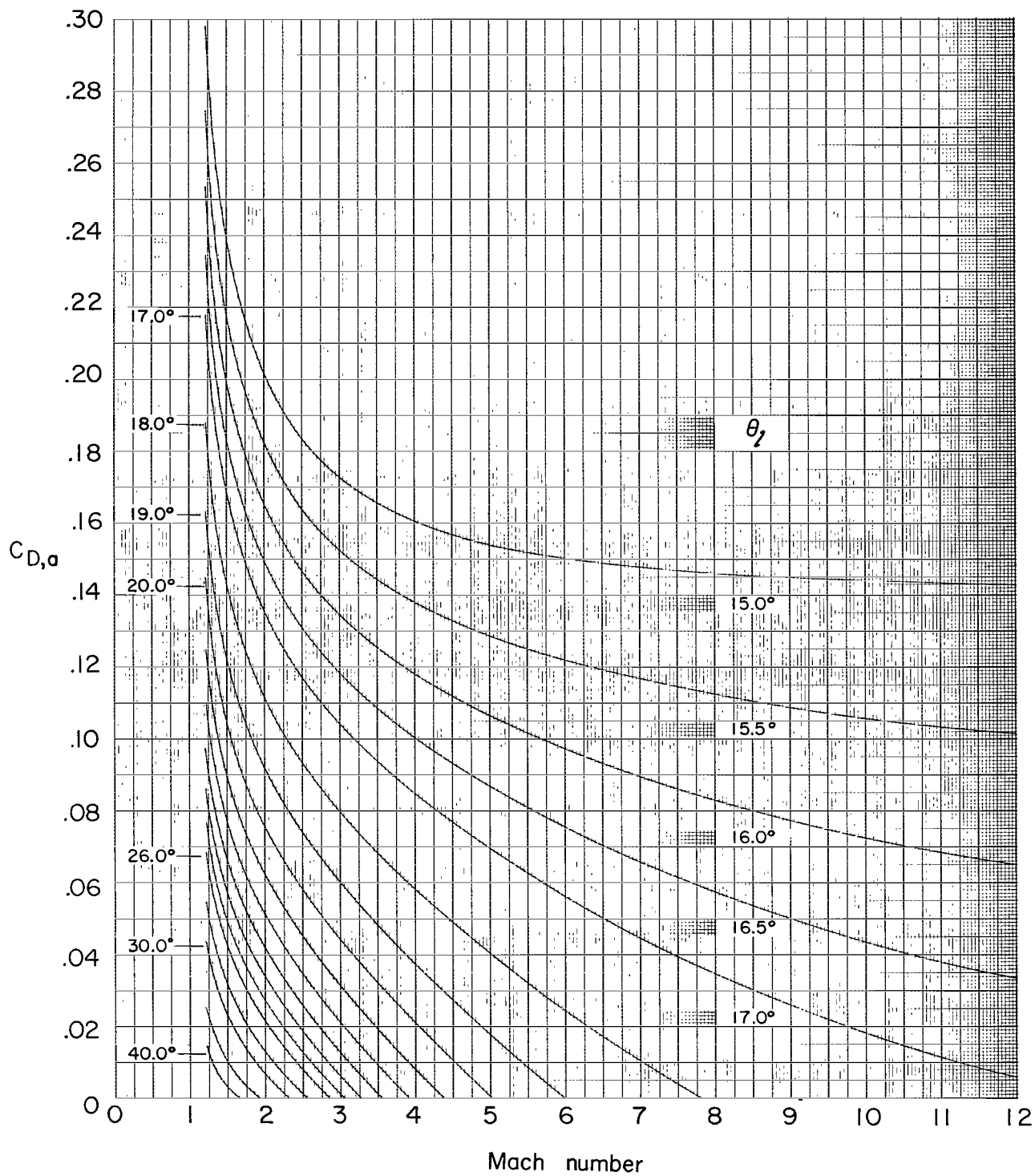
(b) Variation of mass-flow ratio with Mach number.

Figure 8.- Continued.



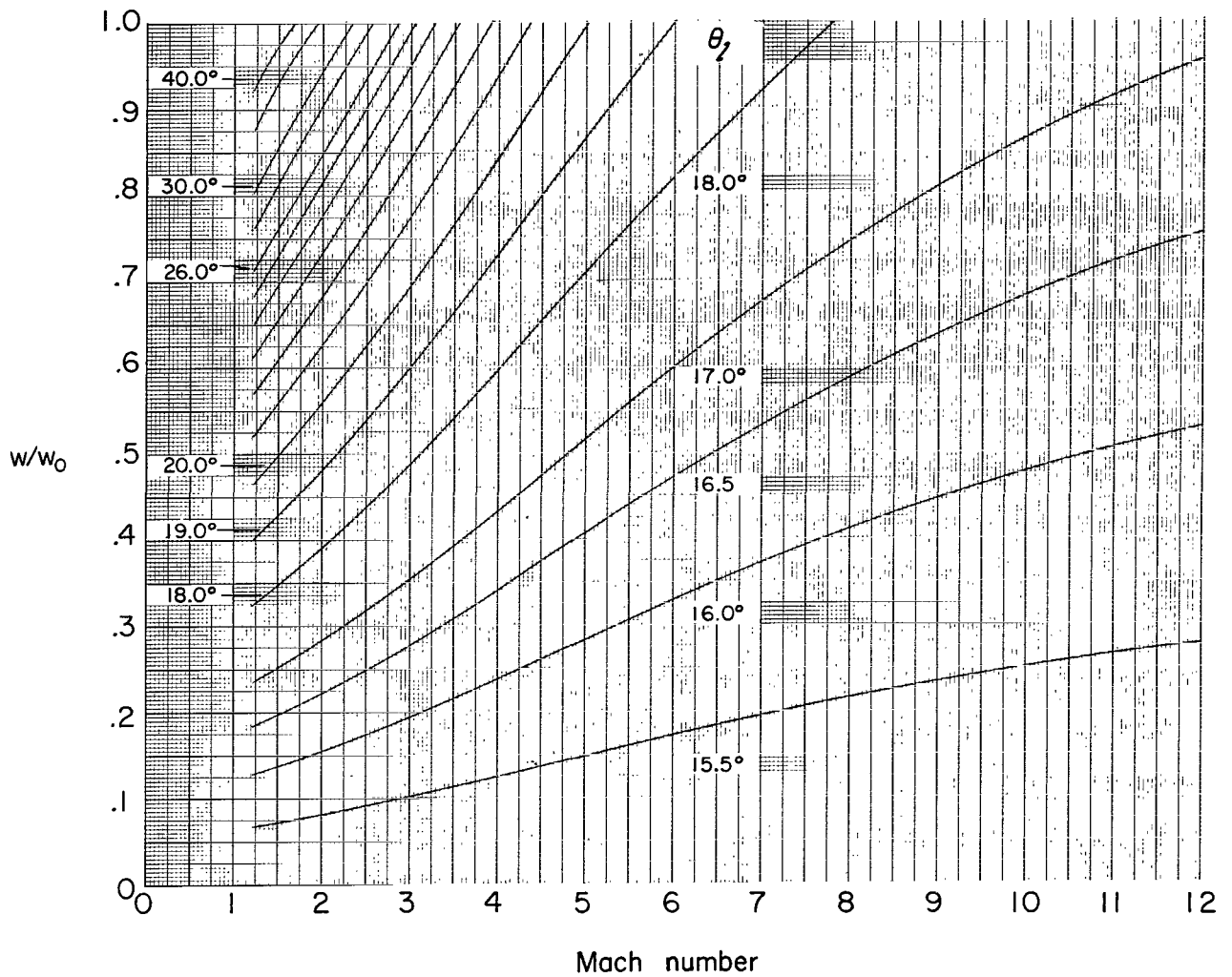
(c) Variation of additive drag with mass-flow ratio.

Figure 8.- Concluded.



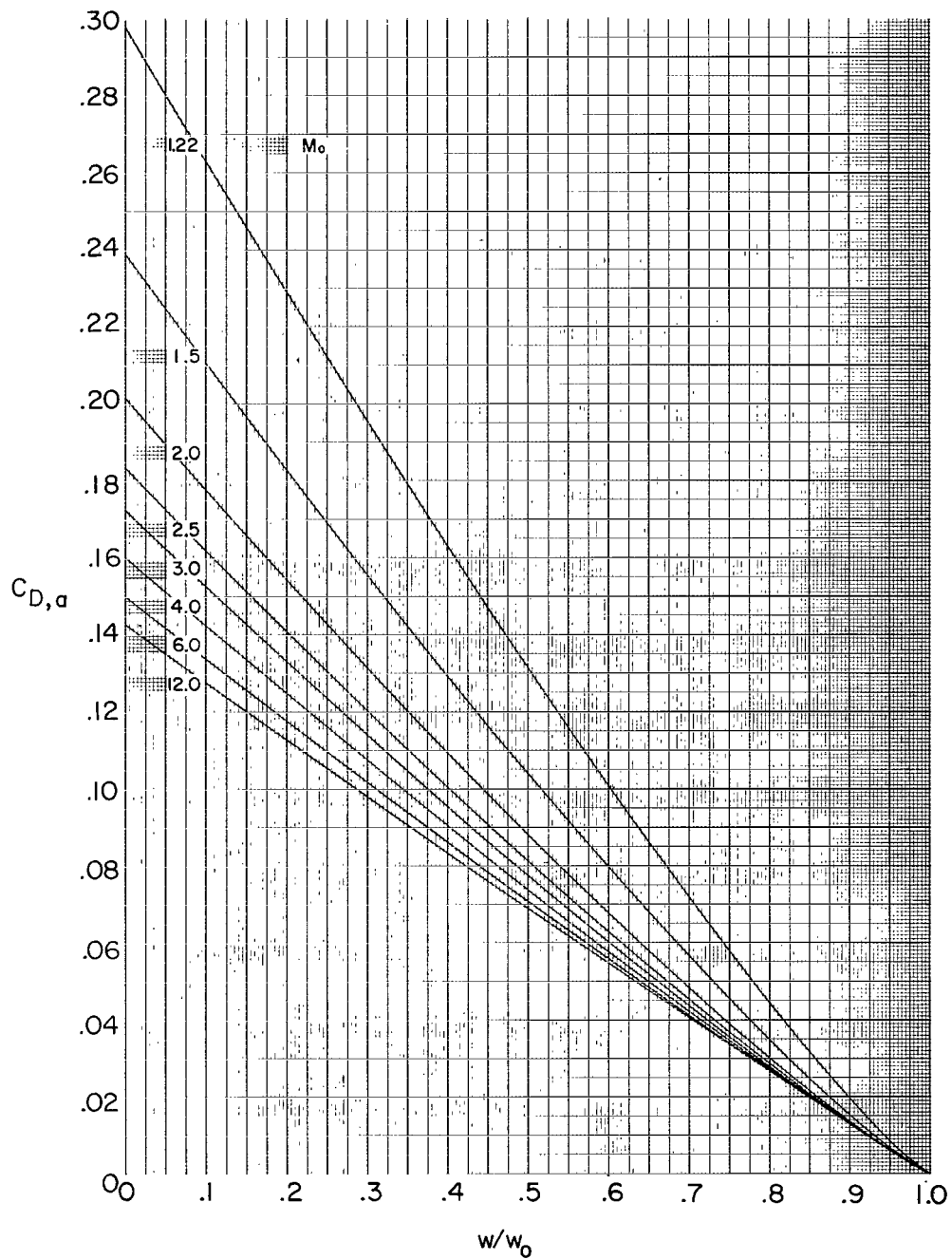
(a) Variation of additive drag with Mach number.

Figure 9.- Variation of additive drag and mass-flow ratio for $\eta = 15^\circ$.



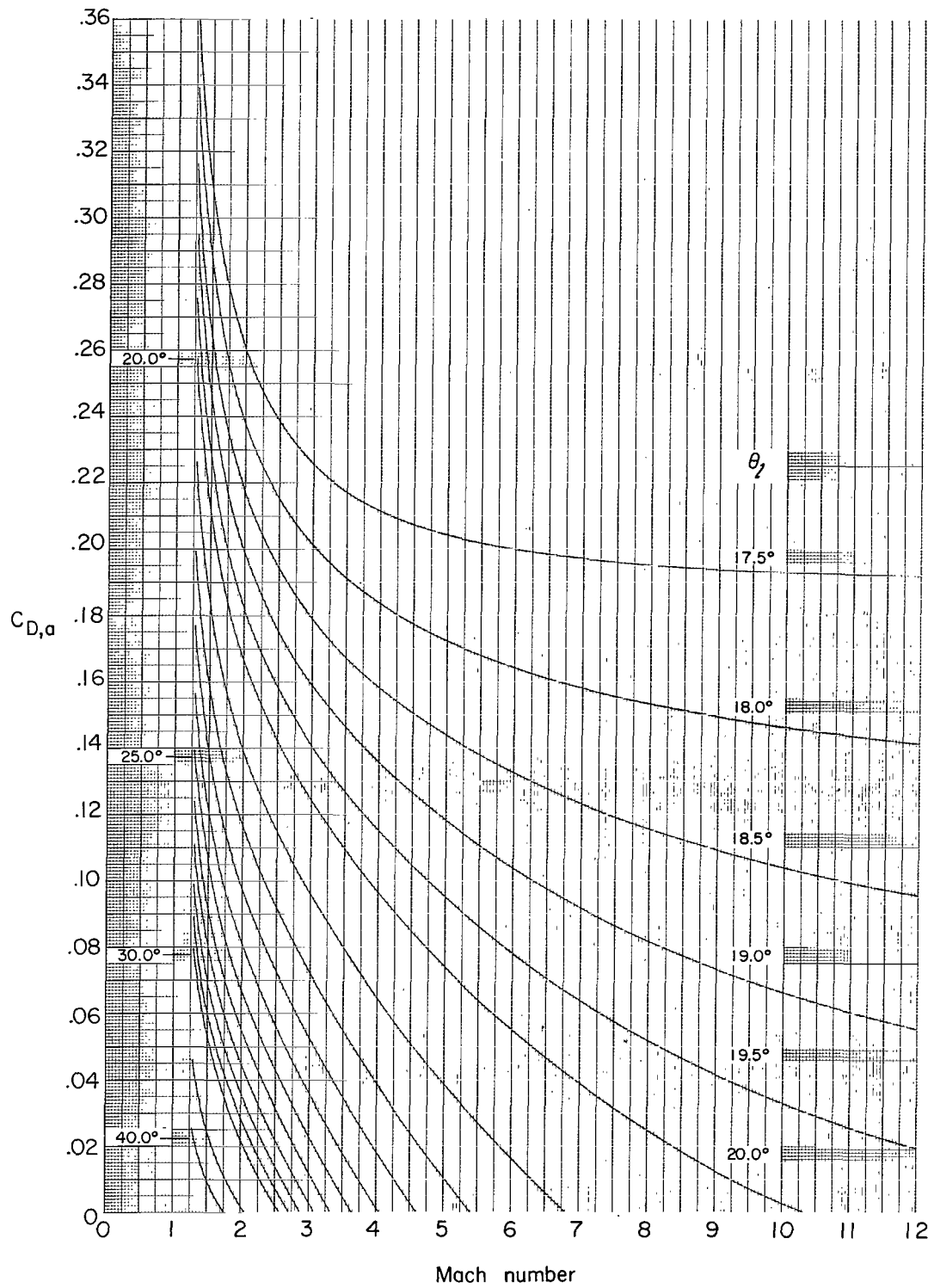
(b) Variation of mass-flow ratio with Mach number.

Figure 9.- Continued.



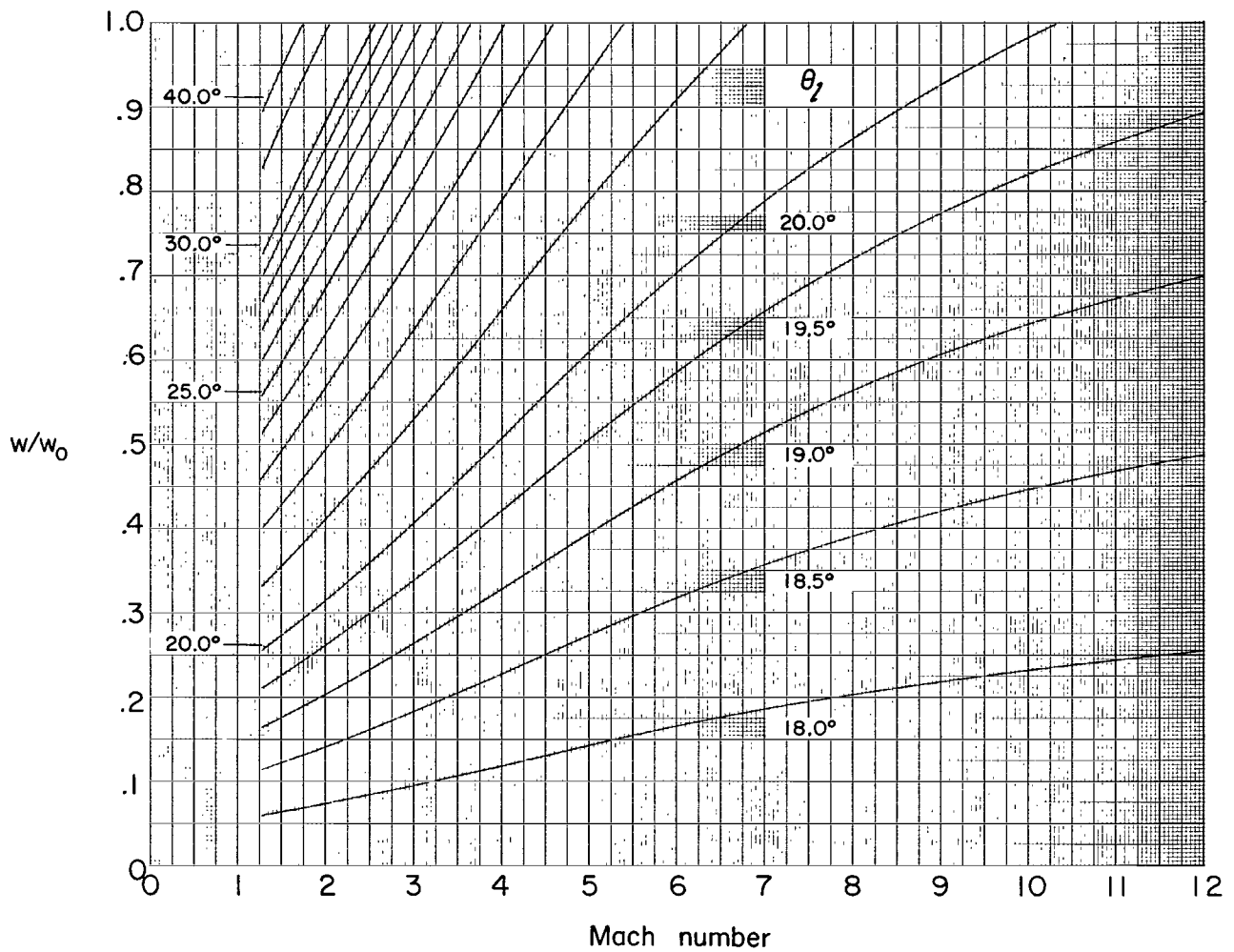
(c) Variation of additive drag with mass-flow ratio.

Figure 9.- Concluded.



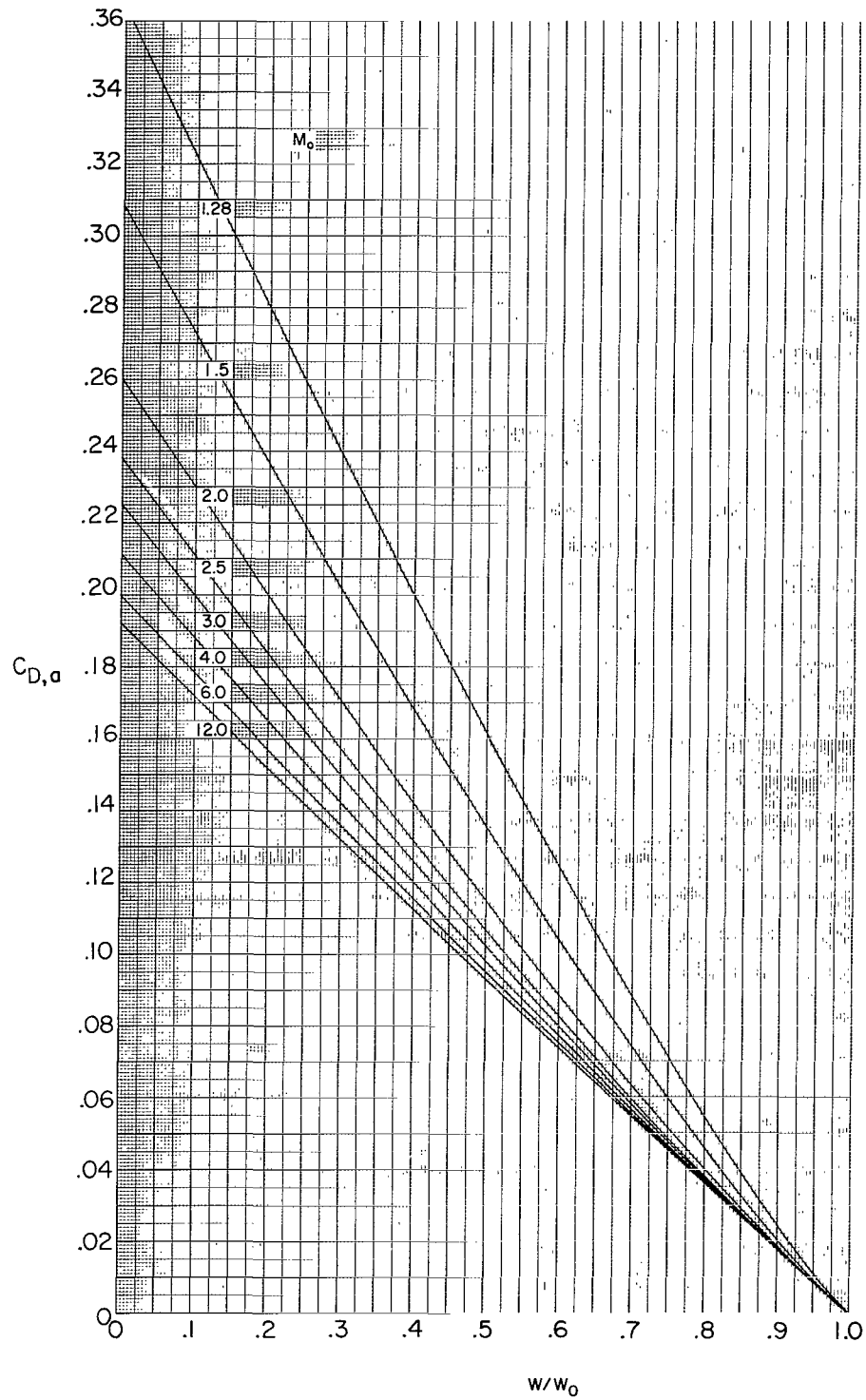
(a) Variation of additive drag with Mach number.

Figure 10.- Variation of additive drag and mass-flow ratio for $\eta = 17.5^\circ$.



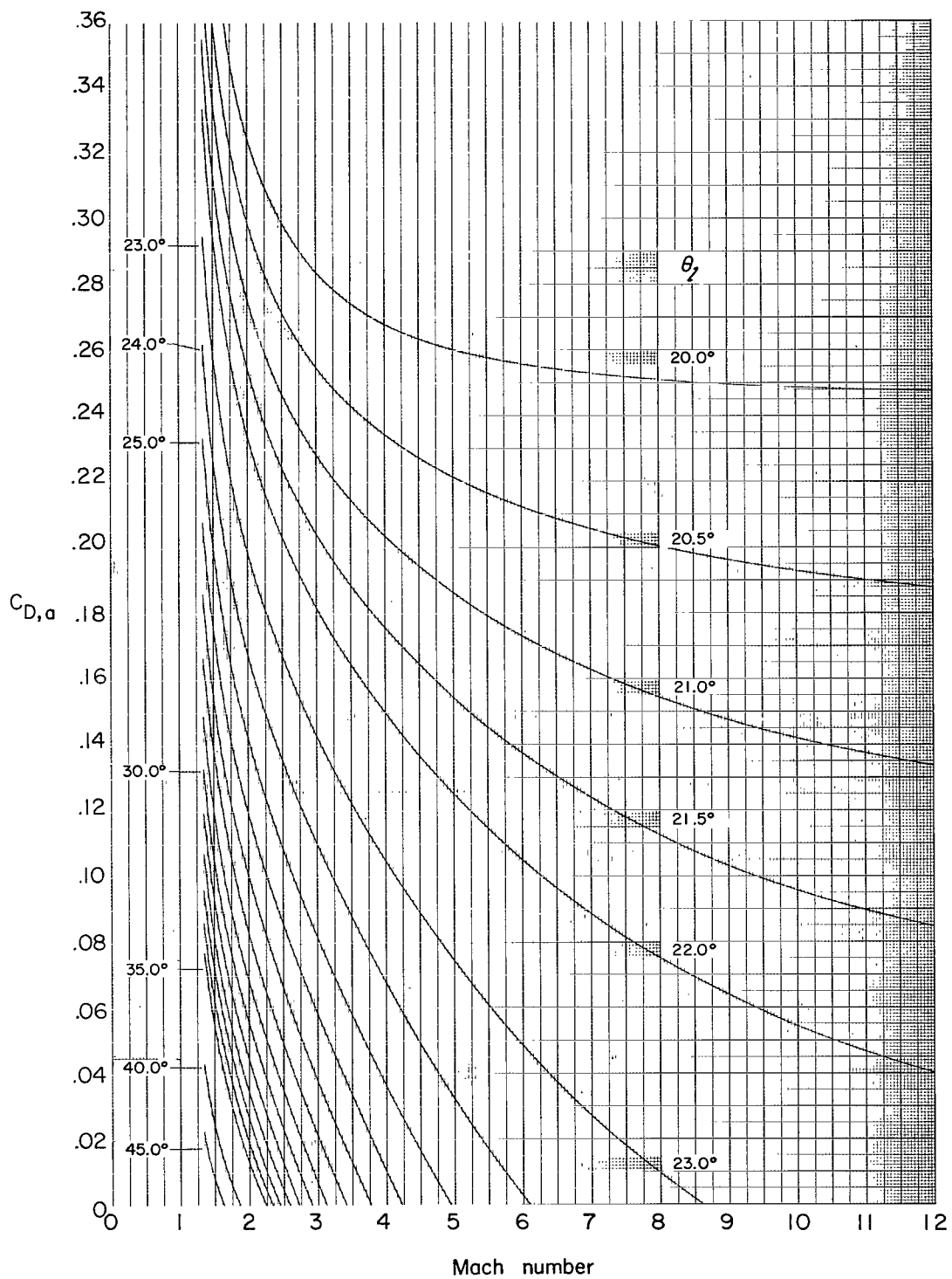
(b) Variation of mass-flow ratio with Mach number.

Figure 10.- Continued.



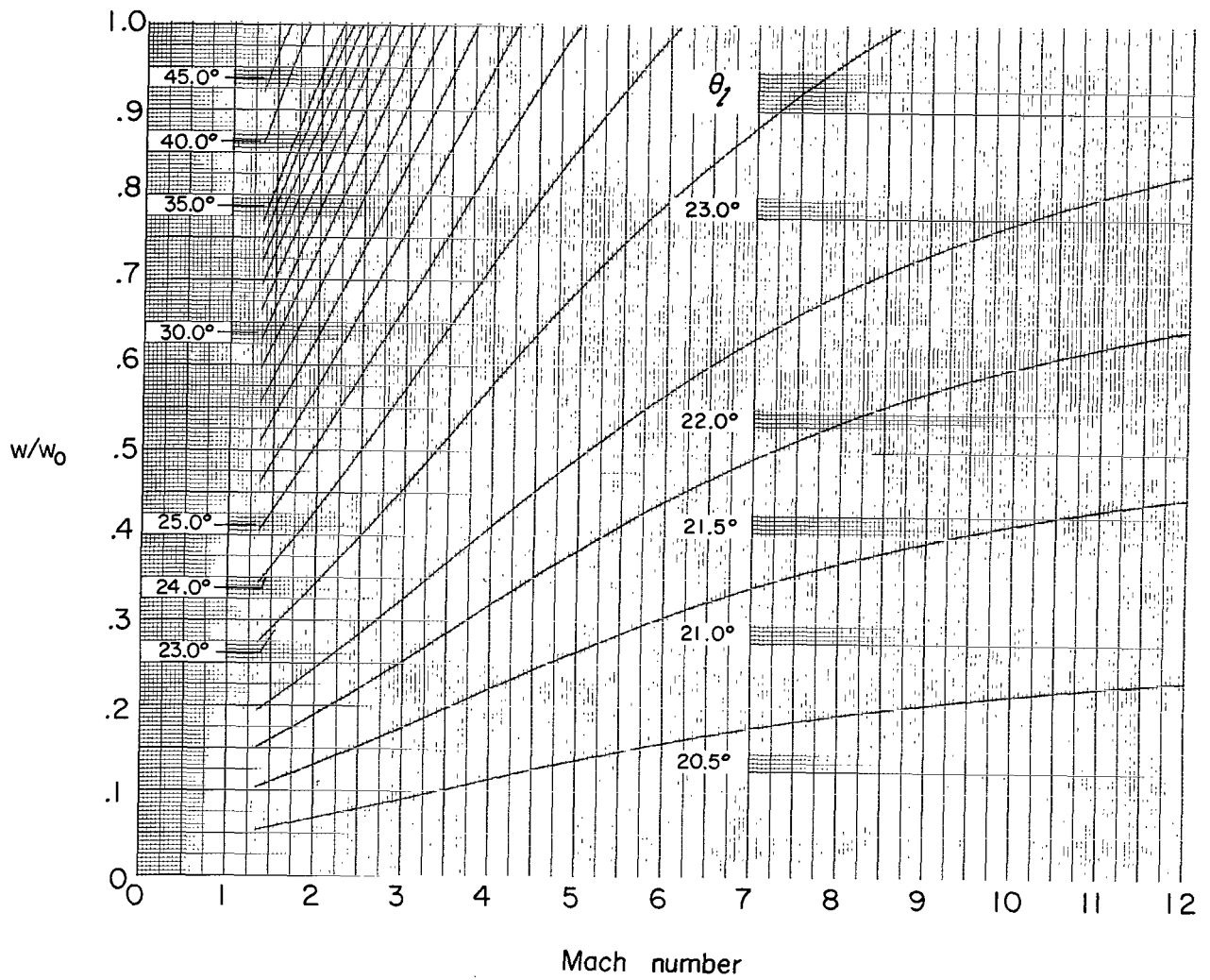
(c) Variation of additive drag with mass-flow ratio.

Figure 10.- Concluded.



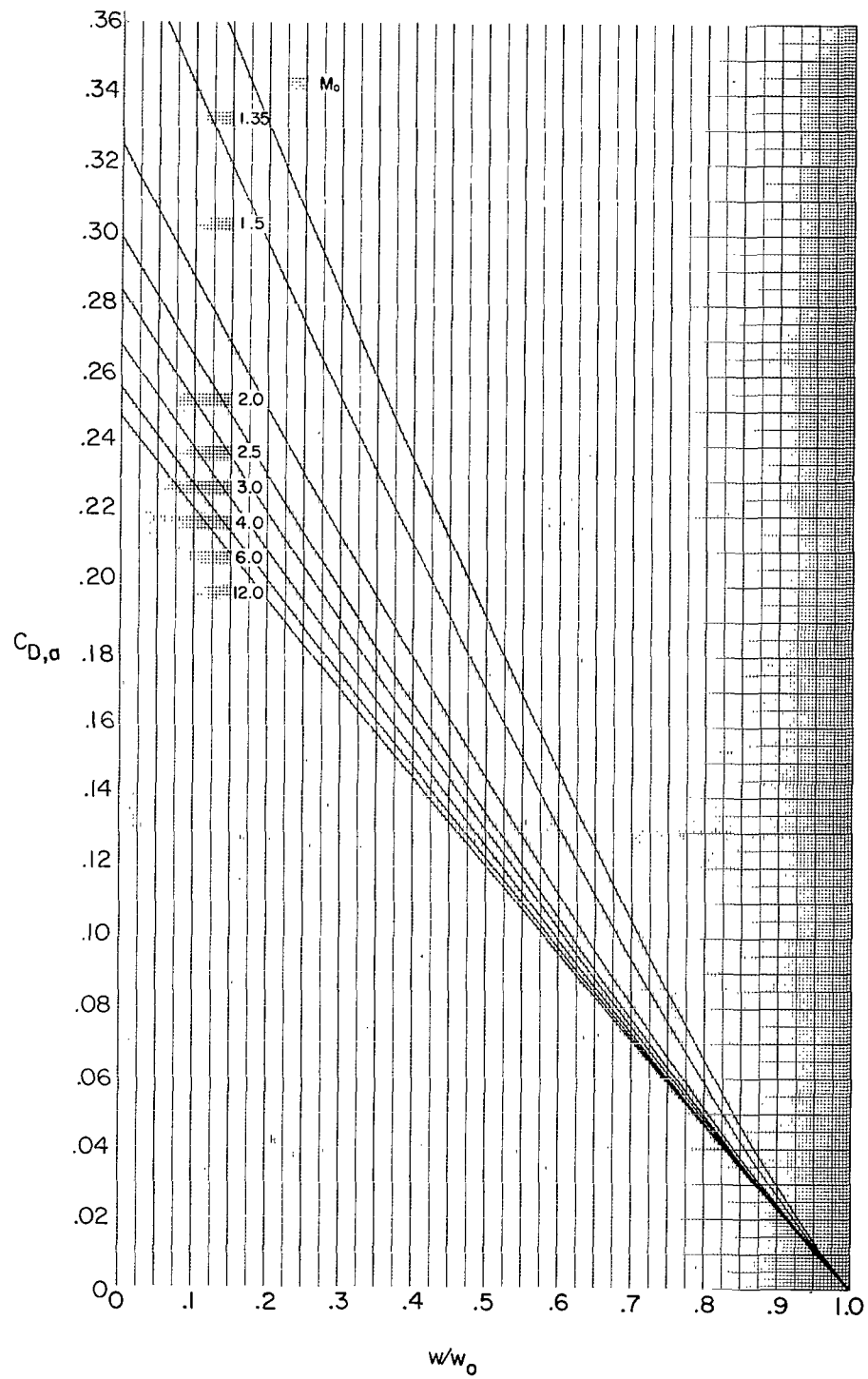
(a) Variation of additive drag with Mach number.

Figure 11.- Variation of additive drag and mass-flow ratio for $\eta = 20^\circ$.



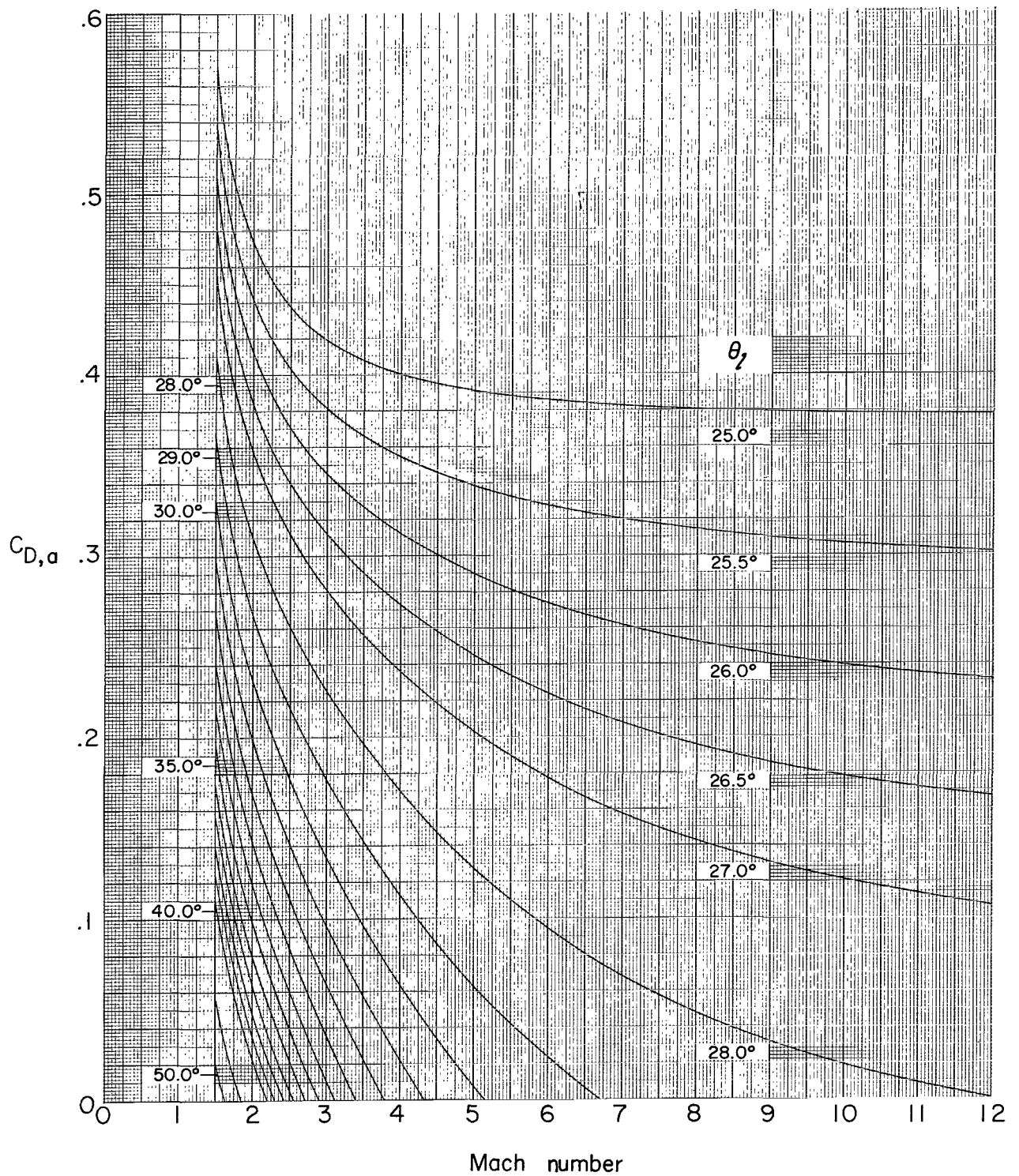
(b) Variation of mass-flow ratio with Mach number.

Figure 11.- Continued.



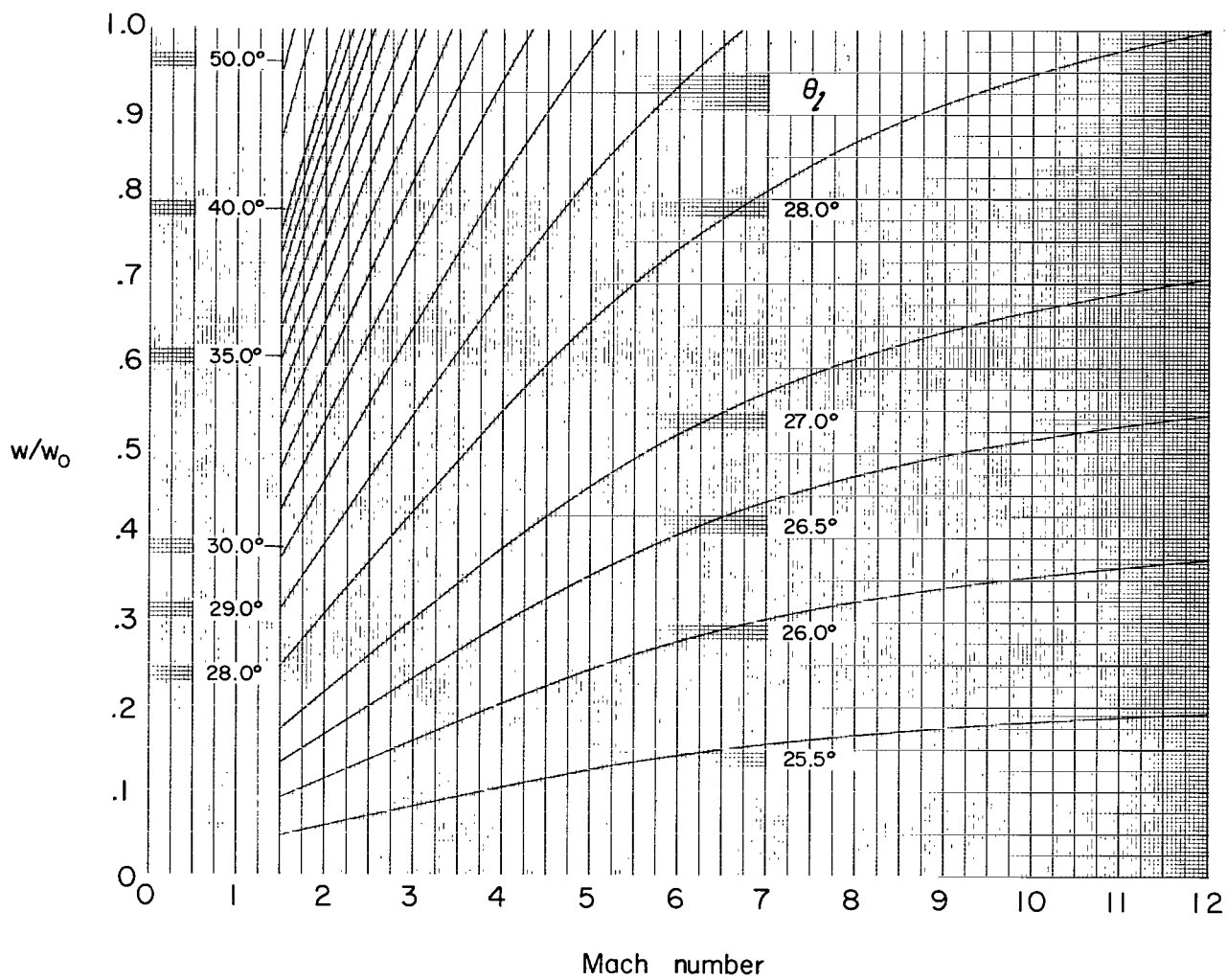
(c) Variation of additive drag with mass-flow ratio.

Figure 11.- Concluded.



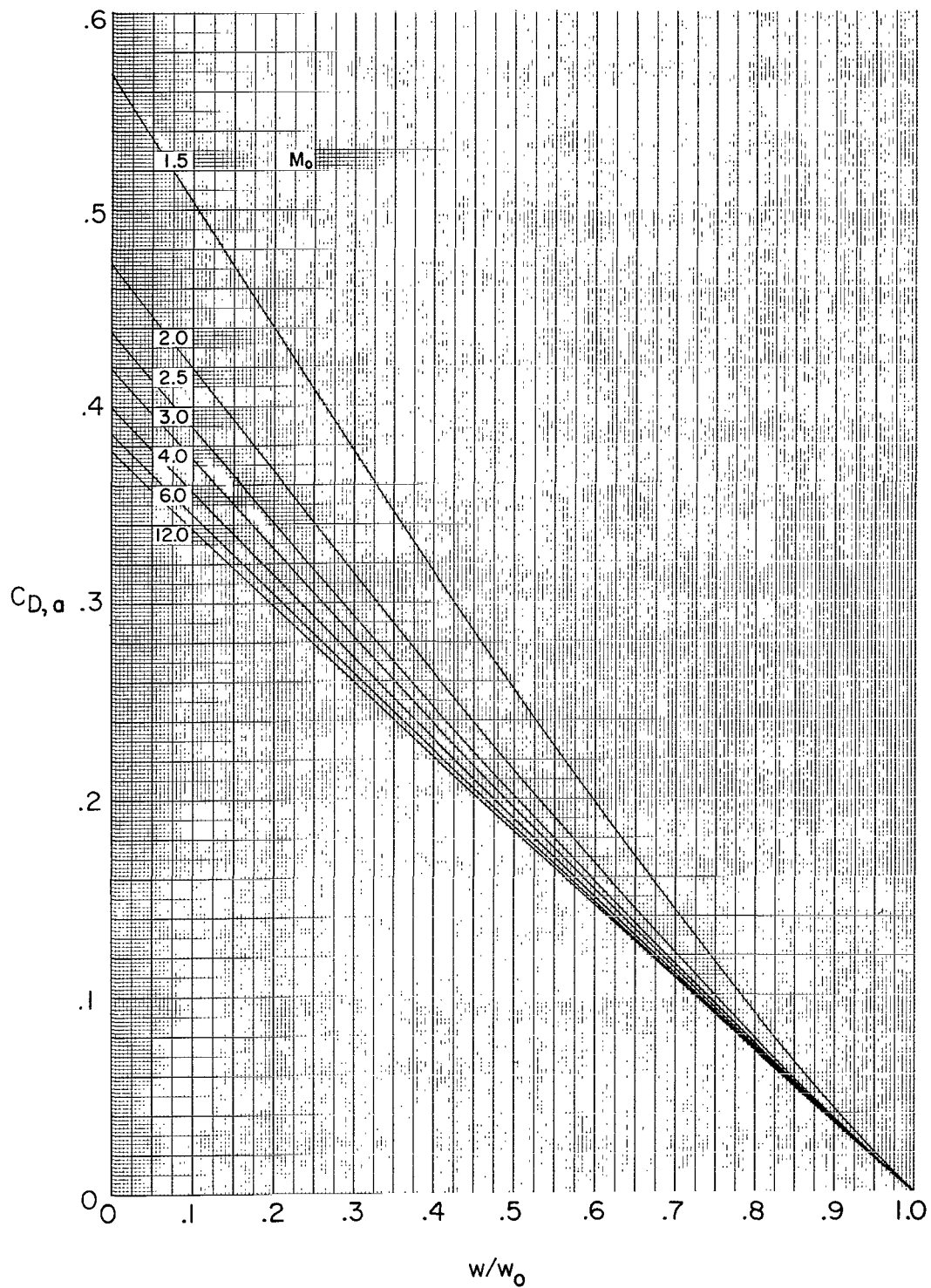
(a) Variation of additive drag with Mach number.

Figure 12.- Variation of additive drag and mass-flow ratio for $\eta = 25^\circ$.



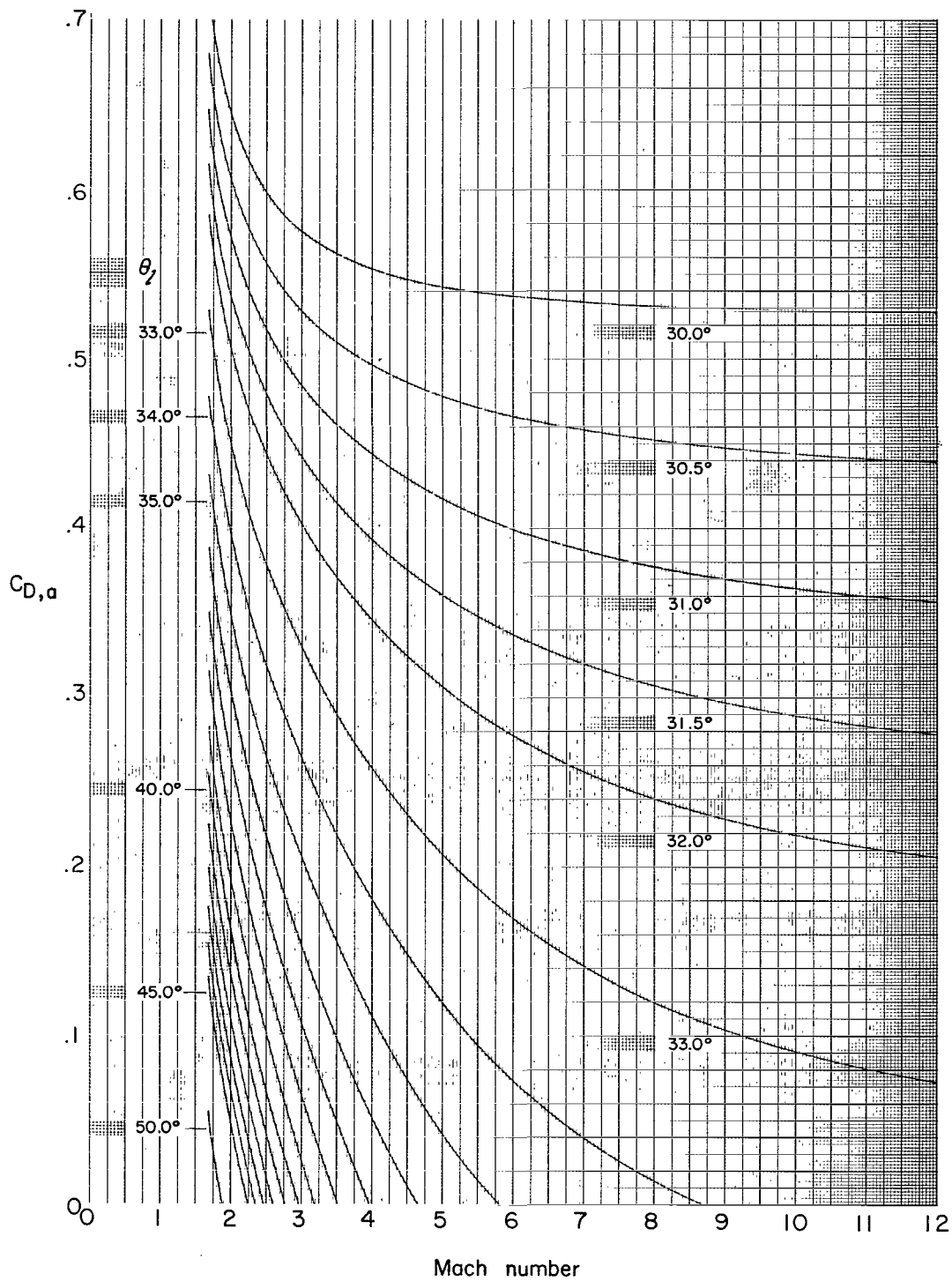
(b) Variation of mass-flow ratio with Mach number.

Figure 12.- Continued.



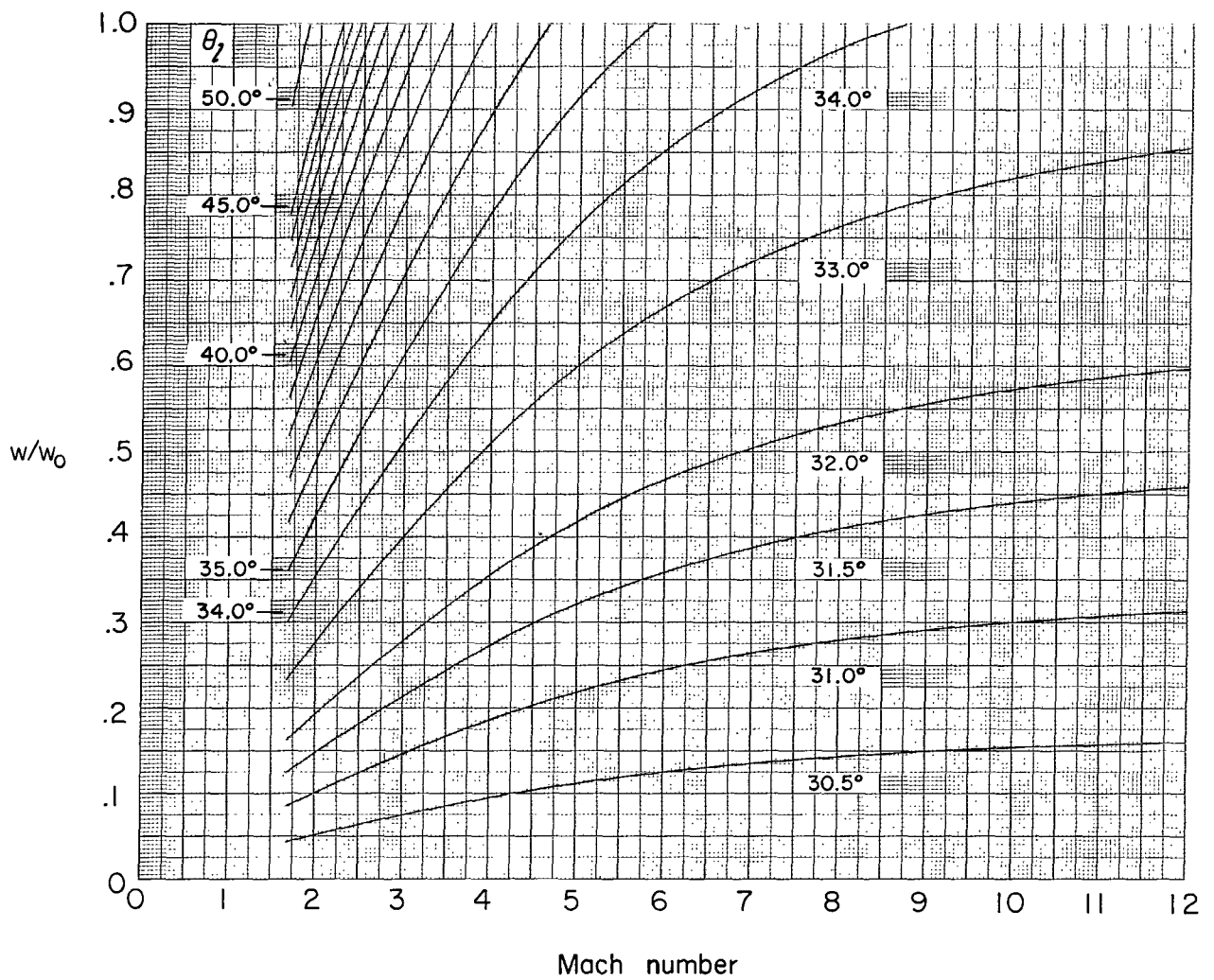
(c) Variation of additive drag with mass-flow ratio.

Figure 12.- Concluded.



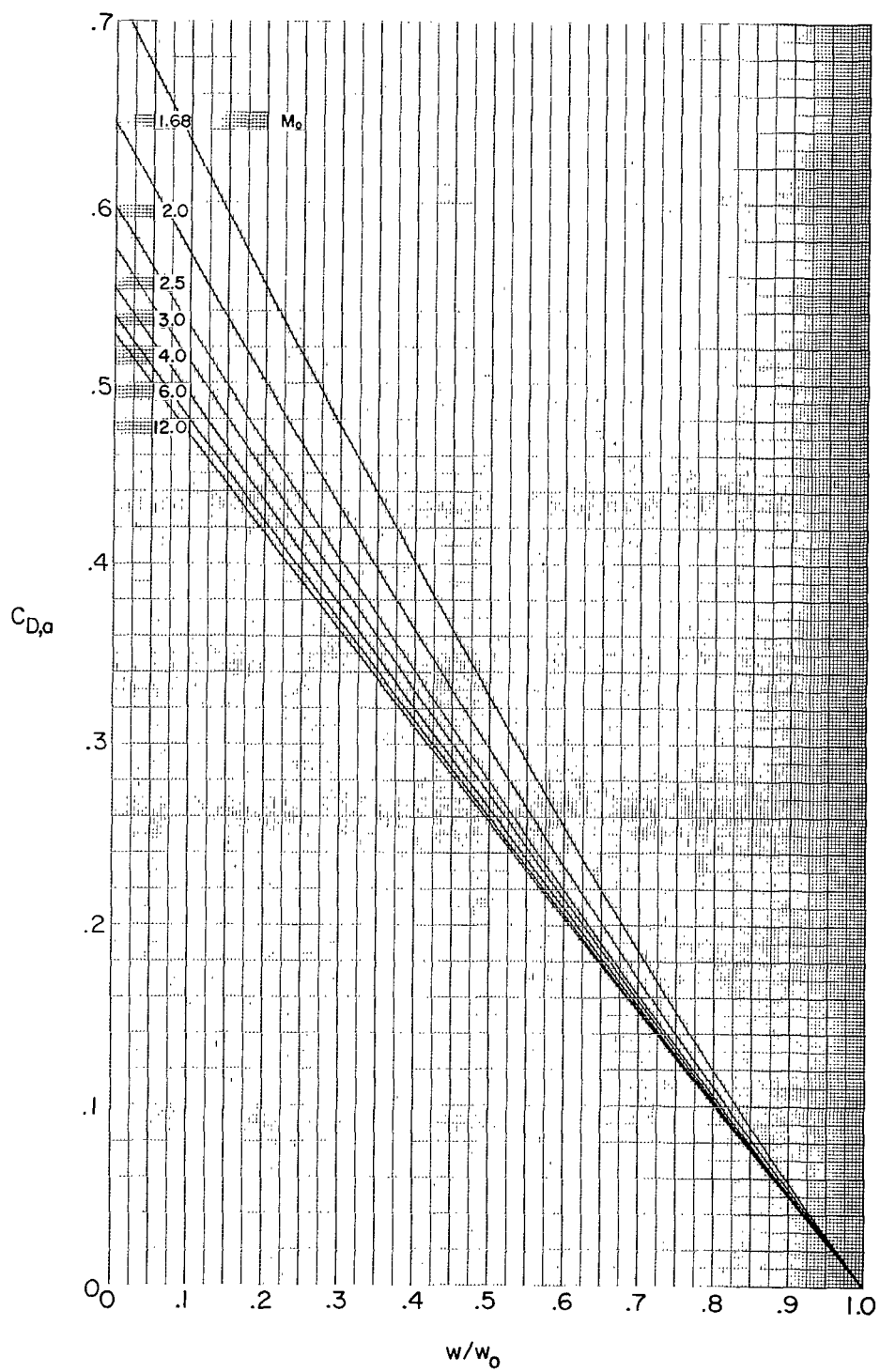
(a) Variation of additive drag with Mach number.

Figure 13.- Variation of additive drag and mass-flow ratio for $\eta = 30^\circ$.



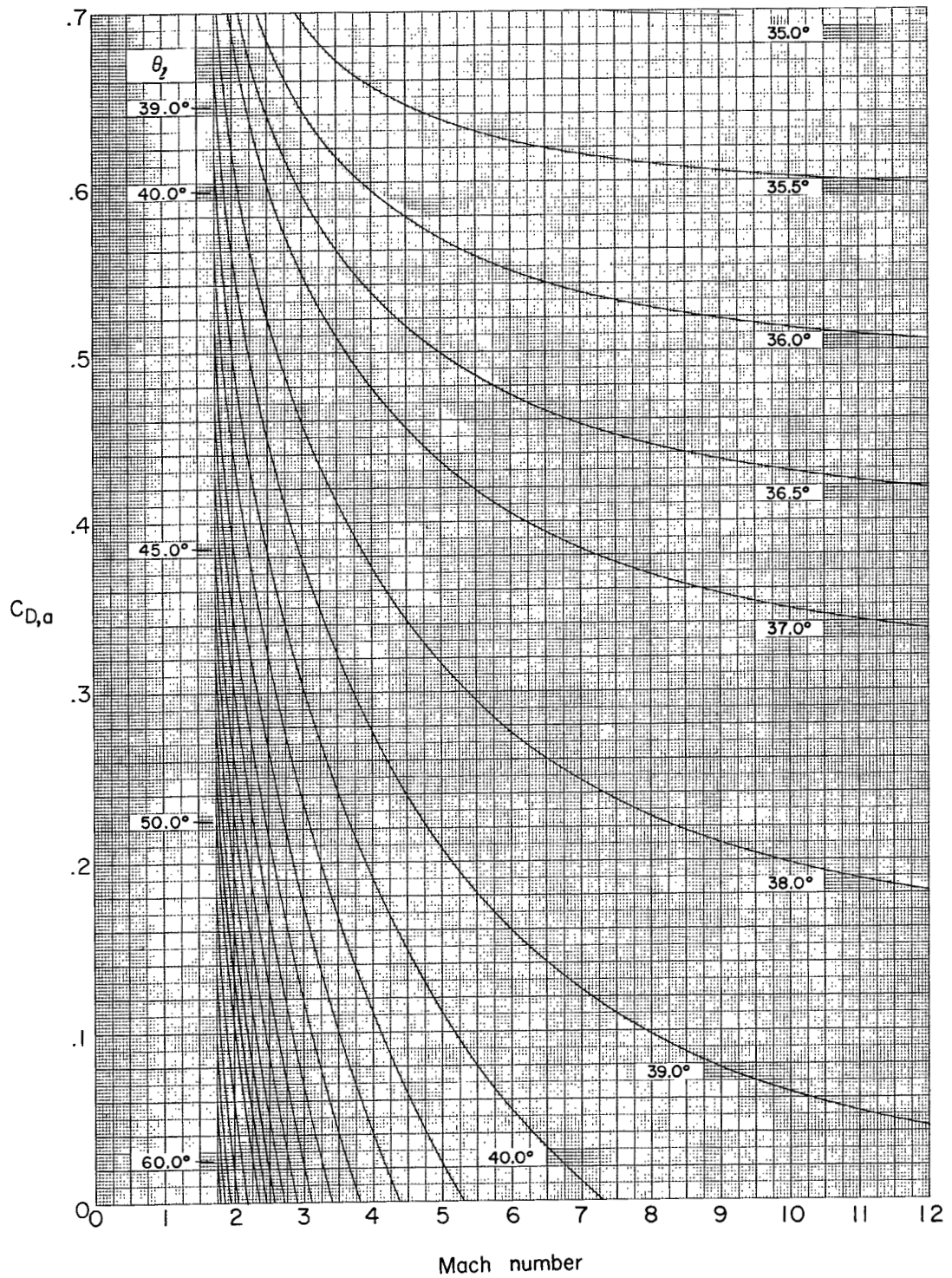
(b) Variation of mass-flow ratio with Mach number.

Figure 13.- Continued.



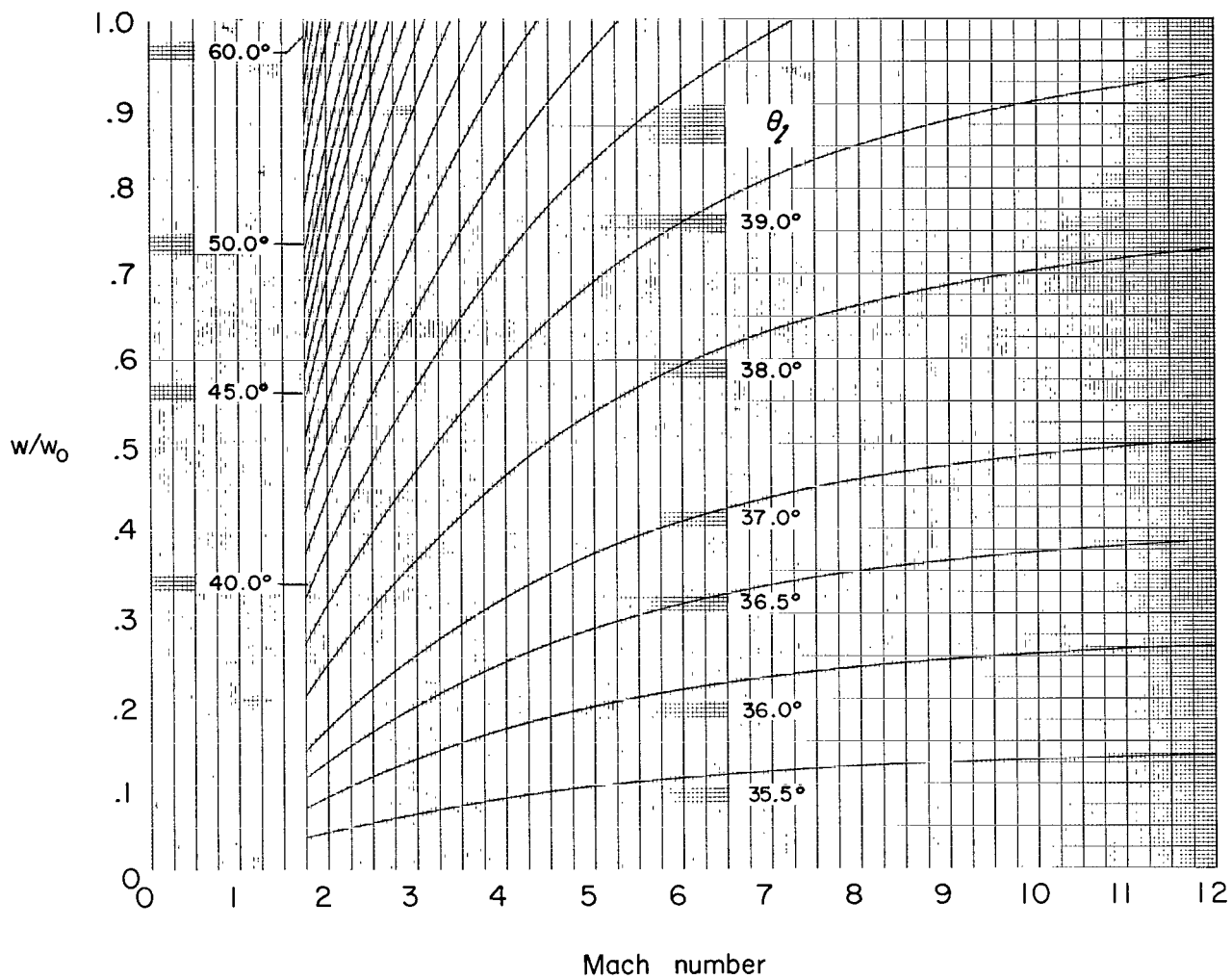
(c) Variation of additive drag with mass-flow ratio.

Figure 13.- Concluded.



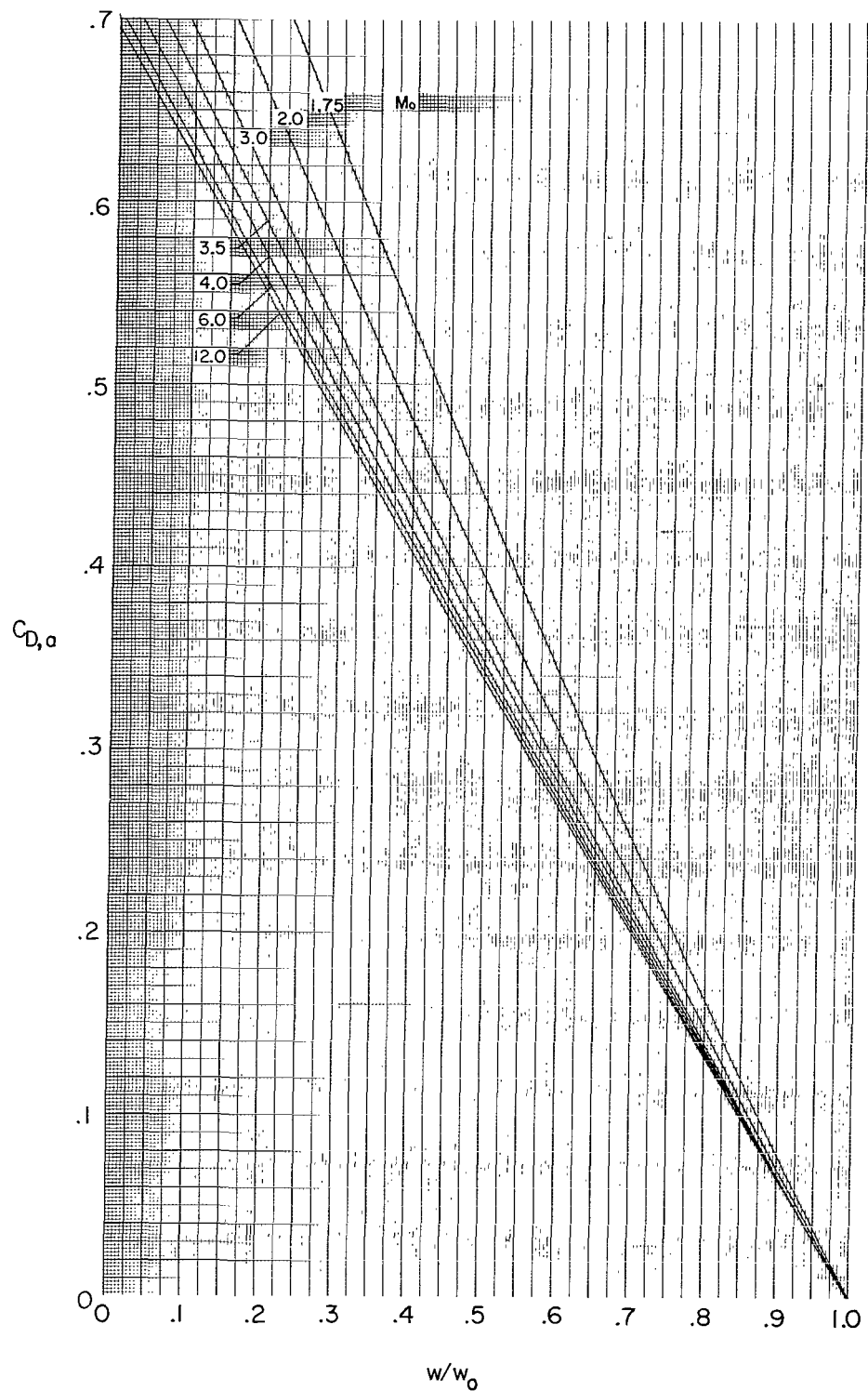
(a) Variation of additive drag with Mach number.

Figure 14.- Variation of additive drag and mass-flow ratio for $\eta = 35^\circ$.



(b) Variation of mass-flow ratio with Mach number.

Figure 14.- Continued.



(c) Variation of additive drag with mass-flow ratio.

Figure 14.- Concluded.

CONCLUDING REMARKS

Working charts are presented giving values of additive drag coefficient and mass-flow ratio for inlets utilizing axisymmetric cones at zero angle of attack. Cone half-angles range from 5° to 35° . The free-stream Mach number ranges from that which will yield sonic flow on the cone surface to 12. Perfect-gas relations are used throughout the calculations.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., March 2, 1966.

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5. Sims, Joseph L.: Tables for Supersonic Flow Around Right Circular Cones at Zero Angle of Attack. NASA SP-3004, 1964.

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